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Cost effectiveness analysis of wingship combatants

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COST EFFECTIVENESS ANALYSIS
OF WINGSHIP COMBATANTS

by

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ABSTRACT

An analysis of the tactical and cost effectiveness of wing-in-ground-effect aircraft (wingships) used as naval surface combatants was conducted. Wingships were compared to current surface combatant warships, carrier based aircraft, and long range bomber aircraft in their projected ability to conduct cruise missile, interdiction bombardment ashore, air defense, and mine warfare missions. Wingships were found to be most effective when a rapid strategic deployment is necessary, such as a response to a regional crisis. Wingships are capable of accomplishing all four missions studied, but are environmentally limited by high sea states and periods of excessive sea loiter. Several technical risk areas are discussed, including lessons learned from Russian wingship experience. The costs of maintaining a fleet of wingships at CONUS bases was compared to the costs of maintaining surface combatant and carrier groups at sea. Projected acquisition and operating costs are higher for wingships than for the other methods, but their tactical and strategic speed advantages offer a unique combat capability.

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I INTRODUCTION

This thesis is an investigation of the cost effectiveness of wing-in-ground-effect (WIG), or wingship, aircraft in the naval combatant role. Today's Navy uses guided missile cruisers and destroyers located in forward areas to deter aggression and, if necessary, conduct combat operations against an enemy force. Naval policy, outlined in *From the Sea*, is built around expeditionary warfare, with forces "swift to respond, on short notice, to crises in distant lands." [Ref.1: p. 3] There is a financial cost involved when stationing a naval force abroad, and in today's shrinking military force structure, there are fewer ships available to conduct these operations.

The wingship provides a possible alternative to forward deployed naval forces. Utilizing the lift enhancement provided by flight-in-ground-effect, a very large aircraft can carry weapons loads similar to those carried on a surface combatant, but at speeds much faster than the surface craft. This revolutionary capability would allow wingships stationed at naval bases in the United States to rapidly respond to a crisis anywhere in the littoral world, without requiring forward deployment of surface forces.

Obviously, there will be a large developmental cost to produce the first combatant wingships. This thesis will

examine the cost of wingship development and production versus the cost of surface warships, and whether the wingship's new capabilities are tactically useful. Chapter II will discuss the aerodynamic principles behind wingship operation and the four design missions. Chapter III will cover the tactical usefulness of the wingship in comparison with current methods for accomplishing the four design missions. Chapter IV will discuss several areas of technical risk inherent in wingship design and operations. Chapter V contains cost estimates and analyses for wingship production and operations, compared to the costs for current surface combatants.

This report will not cover the political aspects of a forward presence doctrine, or the deterrent value of a forward deployed force. America's leaders must decide on a military strategy based upon foreign policy goals, any defined national security threats, and the available military forces. Inclusion of wingships into the naval force will give the national leadership an additional capability with which to decide and implement their military policies.

II WINGSHIP FUNDAMENTALS

A. INTRODUCTION

The two major flight regimes for a wingship are the in-ground-effect cruise and power augmented ram flight, which is used during takeoffs and landings. Both operating modes will be discussed in this chapter. The four design missions will also be defined at the end of the chapter.

The baseline wingship for this analysis is a 1000 ton maximum takeoff weight aircraft, with a fuel fraction of 0.3 and a payload fraction of 0.25. It has an aspect ratio of 3, and is shown in conceptual form in Figure 1.

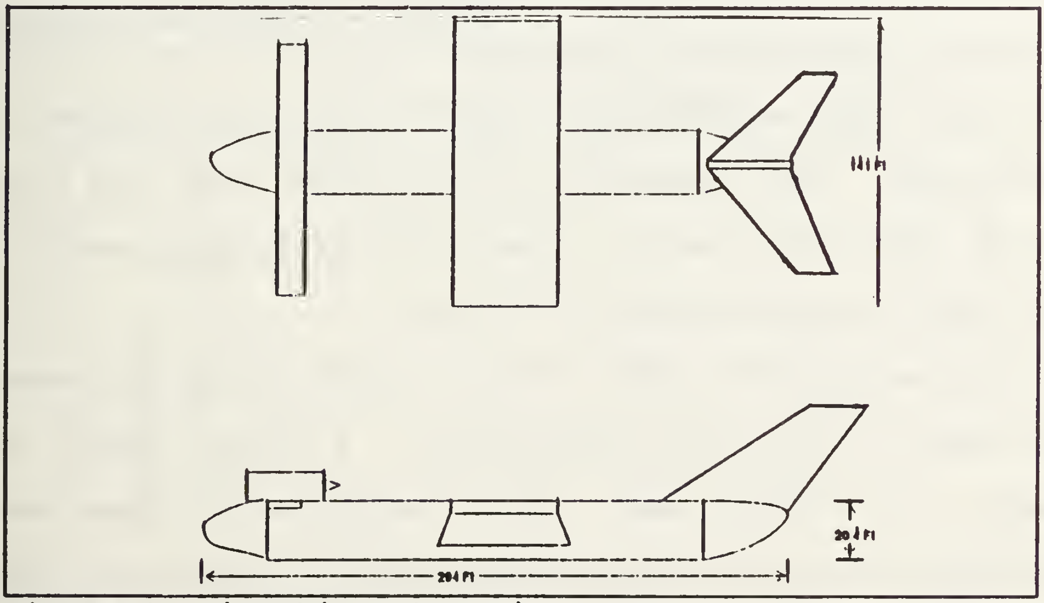

Figure 1: Wingship Schematic

B. IN-GROUND-EFFECT CRUISE

A conventional wing creates lift due to an induced pressure differential between its upper and lower surfaces. In a three dimensional environment, some air spills over each wing tip due to the higher pressure beneath the lifting wing, and lower pressures above it. This spillage creates a wing tip vortex which reduces the wing's efficiency by increasing the drag.

The induced drag coefficient is given as follows:

$$C_D = C_{D_o} + C_{D_i} \tag{1}$$

where

$$C_{D_i} = \frac{C_L^2}{\pi e AR} \tag{2}$$

C_D is the total drag coefficient, C_{Do} is the zero lift, or profile, drag coefficient, and C_{Di} is the induced drag coefficient. The components of the induced drag term include C_L, the lift coefficient; e, the Oswald efficiency factor; and the aspect ratio AR [Ref 2: p. 338].

This expression shows that the induced drag increases as the square of the lift coefficient. A larger aspect ratio reduces the induced drag, since long, slender wings better approximate the ideal infinitely long two dimensional wing.

A wing flying in-ground-effect experiences less induced drag than one out of ground effect. Physically, this is due to the ground plane's interference with the production of the

tip vortices. Weaker vortices rob the wing of less energy, which reduces the loss due to induced drag.

Reference 3 discusses a quantification of the ground effect on a wing determined by Wieselsberger's vortex theory. This theory modifies the induced drag term to include a correction factor σ:

$$C_{D_i}=\frac{C_L^{\,2}}{\pi eAR}(1-\sigma) \tag{3}$$

The correction factor σ is found by

$$\sigma=e^{-2.48(2\frac{h}{b})^{0.768}} \tag{4}$$

where h is the height of the wing above the ground, and b is the wingspan. Graphically, σ is related to the height above the ground as shown in Figure 2.

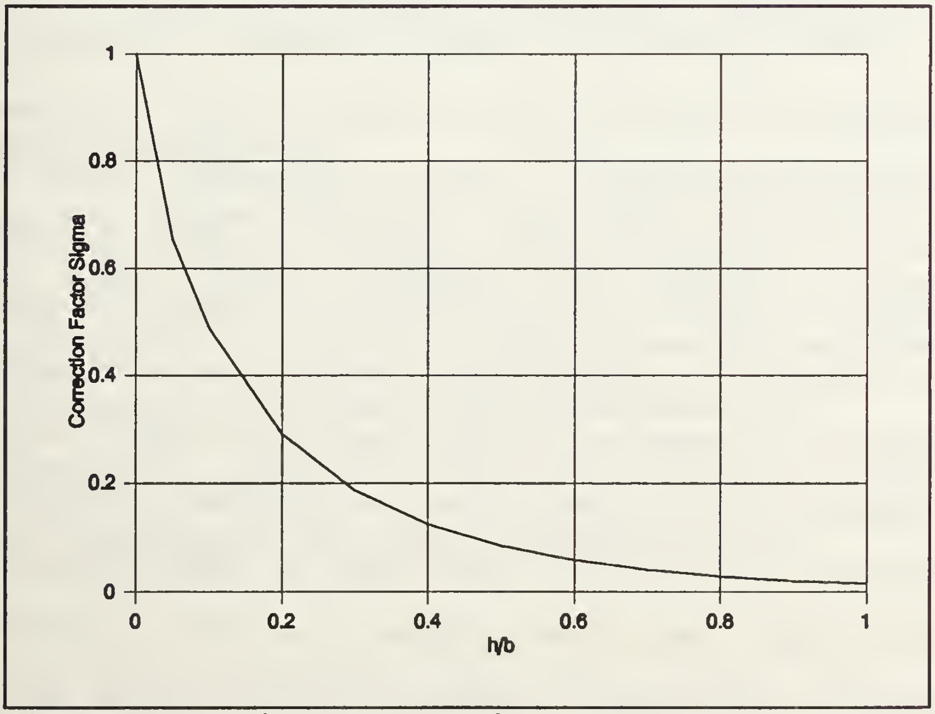

Figure 2: Height Correction Factor

For an example aircraft operating at a C_L of 0.5, with an efficiency factor e = 0.95, and an aspect ratio of 3, the induced drag coefficient as determined by equation (3) is shown in Figure 3.

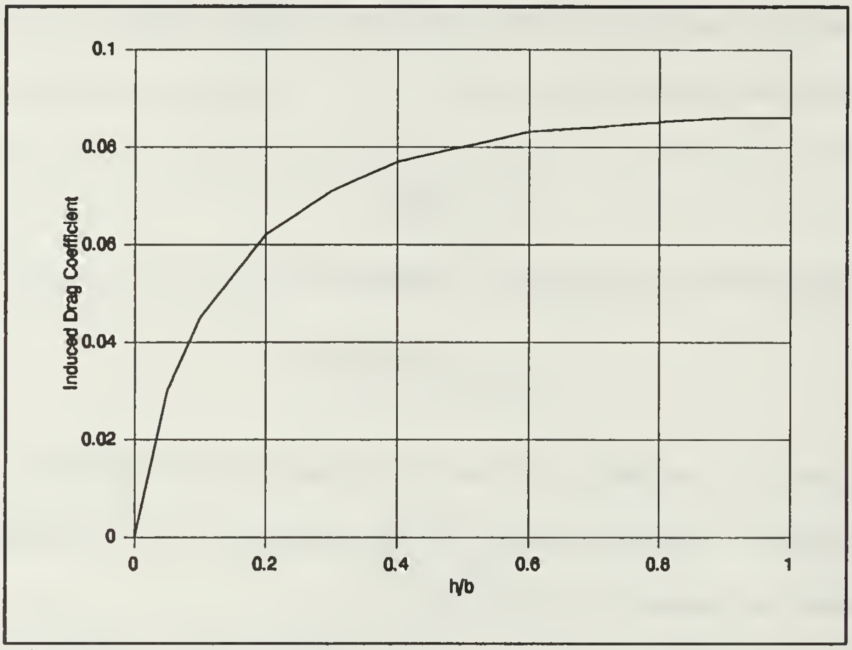

Figure 3: Example Induced Drag

Reference 3 cites work by Ashill, Kida, and Migai, who determined corrections to the Weiselsberger theory for the presence of wing end plates. Figure 4 shows the effect of endplates on the correction factor σ. Endplates retard tip vortex formation by physically blocking the spillage of high pressure air attempting to move toward the upper surface.

Figures 3 and 4 show that an aircraft cruising at a sufficiently low height will have a significantly lower induced drag than one flying out of ground-effect. Aerodynamic efficiency is measured by the ratio of lift to

drag, so any decrease in drag, for the same lift, obviously increases vehicle efficiency. At the very high gross weights envisioned for combatant wingships, the reduction in drag will allow operation with less thrust.

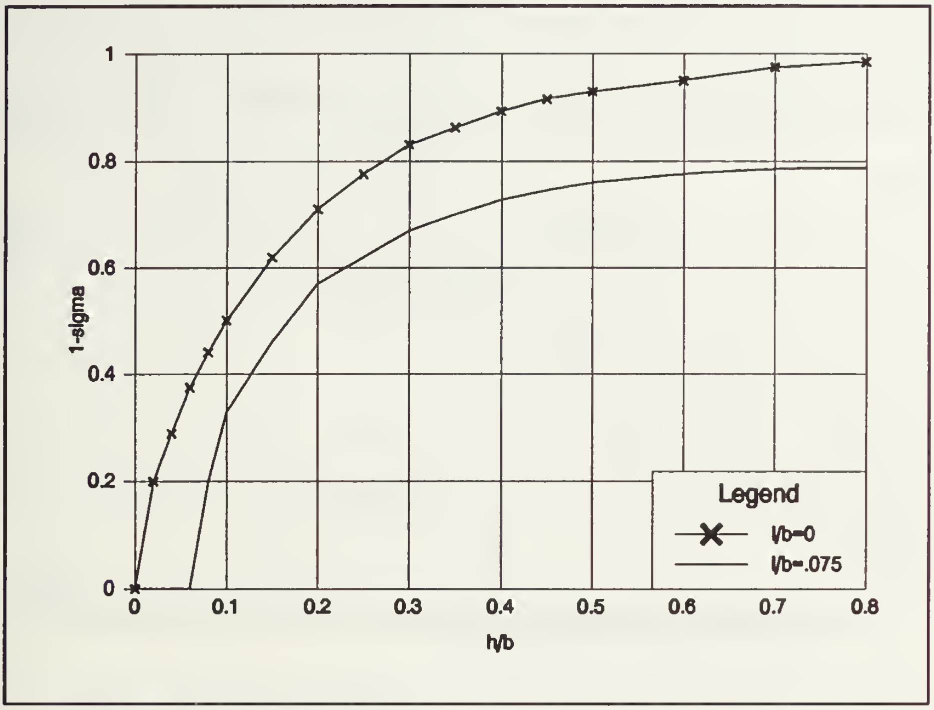

Figure 4: Endplate Effect on Correction Factor

C. POWER AUGMENTED RAM

The power augmented ram (or PAR) flight condition uses the exhaust from forward mounted jet engines to generate additional lift for use during wingship takeoffs and landings. Figure 5 shows a side view of the PAR geometry.

Gallington's work [Reference 3] shows that the under wing pressure coefficient for a PAR configuration is

$$C_P = 1 - \left(\frac{t_2}{h}\right)^2 \qquad \textbf{(5)}$$

and the thrust coefficient is

$$C_T = (1-\cos(\beta))\left(\frac{t_2}{t_1}\right) + \cos(\beta) \qquad \textbf{(6)}$$

where the parameters in equations 5 and 6 are identified in Figure 5.

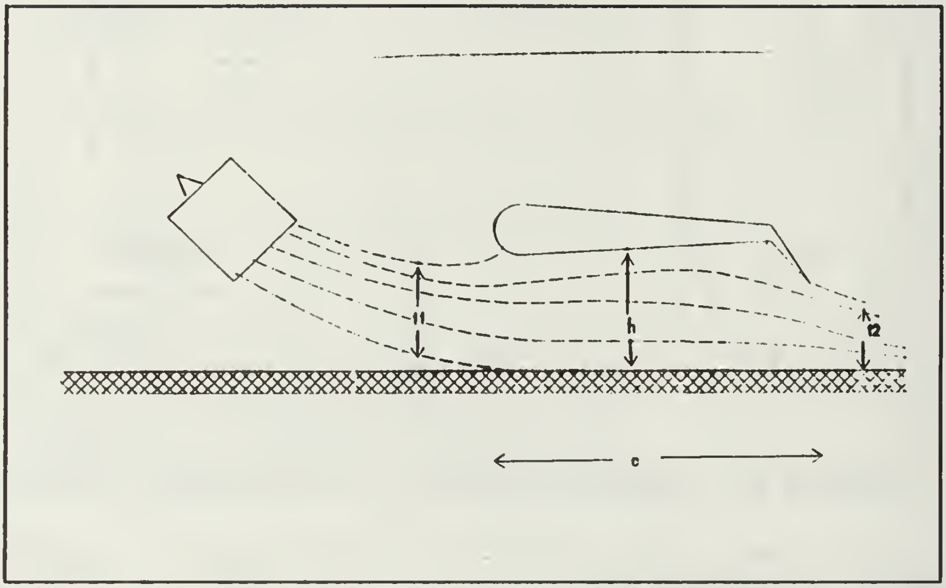

Figure 5: PAR Geometry

PAR performance is usually shown (Ref 4: p. 8) as (L/T)(h/c) versus (T-D)/T. This relates aerodynamic efficiency to excess thrust, which equates to potential forward acceleration capability. This is a measure of takeoff distance required. Figure 6 shows this graphic representation of PAR performance.

Chapter IV contains a discussion of the mechanics of PAR takeoffs and landings.

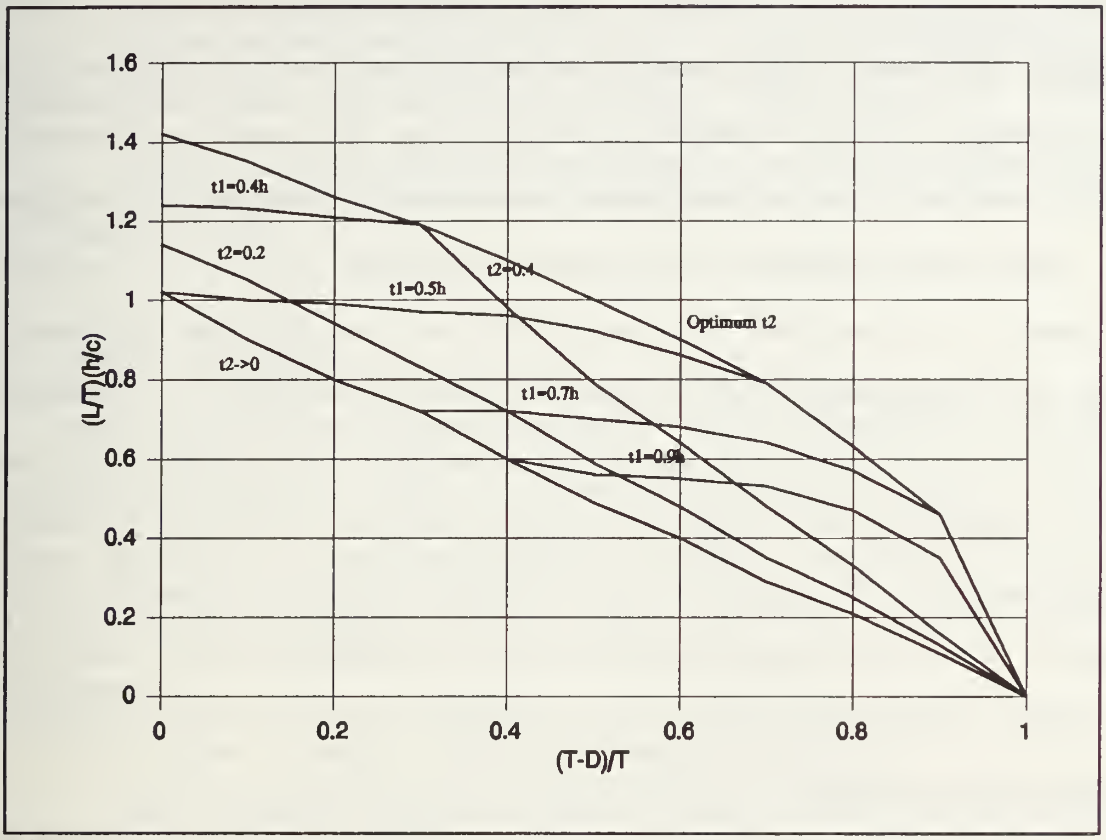

Figure 6: PAR Performance Map

D. CURRENT WINGSHIPS

The former Soviet Union developed several large operational wingships in the 1970s. They built a fleet of ten experimental "ekranoplans", including a 540 ton aircraft called KM. This wingship was approximately 100 meters long, with a 40 meter wingspan. It was used for test purposes for about 15 years. [Ref: 6]

Follow-on Russian wingships include the Orlan and Lun aircraft. The Orlan weighs 140 tons at takeoff, carrying a 20 ton payload 1500 kilometers at a speed of 400 km/hour. It is about 190 feet long, and is normally used as a transport. It is powered by two turbofans mounted on the nose for takeoffs and landings, and a large tail mounted turboprop for cruise.

The Lun aircraft is larger, weighing up to 400 tons at takeoff. It cruises at a velocity between 240 and 300 knots, and has a maximum range of about 3000 kilometers. It normally cruises at a height of one to four meters above the water, and is capable of out-of-ground-effect flight up to altitudes of 3000 meters. The Lun is 242 feet long, with a wingspan of 144 feet. It is used operationally as a transport, for search and rescue, and intelligence sources have said it was capable of carrying antiship missiles [Ref. 7: p. 62].

Russian wingship designers identified several key problem areas encountered in their ekranoplan experience [Ref. 6]:

1. A high L/D ratio is necessary for the wings and the wingship as a whole in both cruise and PAR operating modes.

2. The wingship must have a high aerodynamic efficiency during takeoff.

3. The aircraft must be designed for stability during all operating modes, to include sea-sitting and transient modes.

4. Seakeeping during takeoffs and landings is important.

5. Structural strength to withstand the high takeoff and landing loads must be provided, without a huge weight penalty.

6. The engines must be protected against water ingestion.

7. "Special devices" for safe operations at low altitude must be developed. This probably includes radars to detect potential obstacles, and/or endplates designed to absorb wave impacts.

8. Special experimental facilities, such as high speed tow tanks and wind tunnels that simulate ground-effect flight without the usual tunnel wall boundary layer, must be built.

9. Combined hydrodynamic/aerodynamic research methods are required. These include large model tests, simulations, and full scale tests.

E. DESIGN MISSIONS

There are several design missions to be considered for the combatant wingship. Four of these missions are studied here. These include the cruise missile carrier, the Naval Tactical Missile System (NTACMS) carrier, mine warfare, and air defense missions.

1. Cruise Missile Carrier Mission Scenario

The wingship deploys from a base in the United States to the northern Persian Gulf, refueling as necessary. It establishes data links with national intelligence sources (such as satellites) to receive targeting data, and launches Tomahawk cruise missiles against air defense units, command and control sites, ballistic missile launchers, or other fixed targets. The wingship remains on-station until relieved by a surface ship, the crisis is resolved, or all targets are destroyed. Wingships conduct at sea replenishment of fuel, missiles, and crew members as necessary.

2. NTACMS Carrier Mission Scenario

Again, the wingship deploys to a crisis area from a base in the United States. In conjunction with early warning aircraft and other tactical intelligence sources, the wingship launches NTACMS missiles against massed armored formations, critical mobile targets, and forward area refueling points (FARPs). Missile launches will occur from a sea-sitting position, and the wingship will relocate after every three or four volleys. The wingship will conduct replenishment at sea as necessary. It will remain on station as long as required.

3. Mine Warfare Mission Scenario

The wingship again deploys from United States bases to a crisis area, such as North Korea or the Persian Gulf. For an offensive mission, the wingship lays mines in the designated target area and either returns to a nearby friendly base, returns to its CONUS base, or remains in the target area for follow-on missions. For a defensive mission, the wingship rendezvous with a task group, where it refuels, rearms, and recrews. It then flies ahead of the task group to detect, locate, tag, or destroy any enemy mines. It uses electronic devices or remotely operated vehicles to detect and locate the mines, and expendable ordnance to destroy them.

4. Air Defense Mission Scenario

The wingship deploys to a crisis area and positions itself at sea along enemy air avenues of approach. Radar

configured air defense wingships identify and acquire enemy aircraft, and the missile wingships engage them with long range surface to air missiles. Both wingships reposition frequently to reduce susceptibility to enemy attack. They remain in the area of operations until relieved by other air defense systems, or upon air supremacy. Wingships will rotate to nearby bases or task groups for replenishment as necessary.

The next chapter will analyze the tactical usefulness of the wingship in these four missions in contrast to current methods for performing these missions. Modern tactical principles will also be discussed, along with their applicability to wingship operations.

III TACTICAL ANALYSIS

A. INTRODUCTION

The determination of the feasibility of combatant wingships requires a study of the tactical principles that would direct their employment. Although specific tactics would be developed for the use of this revolutionary weapons system, the basic tactical principles would hold, and would drive the formulation of specific tactics.

This section will analyze the advantages and disadvantages of wingship employment in the four missions of interest. These attributes will be compared to the advantages and disadvantages of the current systems used to accomplish the same missions.

For the purposes of the tactical analysis, several assumptions are necessary. They will be considered in greater detail in other sections of this report. First, it is assumed that the sea and weather states are adequate for both wingship, conventional ship, and missile operations. Wingship fire control accuracy and rates of fire for similar type weapons are assumed to be the same as those for surface ships.

The tactical analysis will consist of an examination of the tactical principles governing seaborne combat operations, the proposed wingship weapons systems configurations and

loadings, a comparison of wingship effectiveness versus the effectiveness of current methods, and finally a discussion of the strategic and operational capabilities of the wingship combatant vehicle.

B. TACTICAL PRINCIPLES

Successful employment of a naval weapons system is based upon several tactical principles. Since ships (and presumably wingships) rarely operate alone, they are governed by collective, or fleet, tactics. Five generally accepted tactical principles are scouting (or reconnaissance), attack effectively first, counterforce, staying power, and maneuver (or mobility).

1. Scouting

Scouting consists of "acts of search, detection, tracking, targeting, and enemy damage assessment, including reconnaissance, surveillance, signals intelligence, and all other means of gathering information that may be used in combat" [Ref. 8: p. 288]. Modern fleets perform these tasks with radar, signal intercept and direction finding, satellite imagery, and visual detection. A successful scouting effort results in early detection of the enemy and targeting solutions that allow for an effective first attack.

2. Attack Effectively First

Modern missile systems travel very quickly and can deliver catastrophic damage after hitting a target. If one

side of an engagement can mount an effective first attack, it can significantly deplete the opponent's force before it can launch its own attack. Missile attacks are "pulsed", versus the continuous nature of gunfire attacks. During circumstances of pulsed power, a side that attacks effectively first can overcome a 2:3 combat power deficit. [Ref. 8: p.272]

3. Counterforce

Counterforce is "the capacity to reduce the effect of enemy firepower" [Ref. 8: p. 287]. In this context, counterforce refers to defensive weaponry, electronic countermeasures, and staying power (addressed in the next section). Defensive missiles, close-in weapon systems (such as Phalanx), and electronic missile countermeasures are used to defeat an enemy missile attack.

4. Staying Power

Staying power is "the capacity to absorb damage and continue fighting with measurable effectiveness" [Ref. 8: p.289]. Armor, compartmentalization, and structural design contribute to a vehicle's staying power. Normally an increase in staying power requires an increase in vehicle weight. The Iowa class battleships are examples of ships with very high degrees of staying power.

5. Maneuver

Maneuver is "movement to achieve a tactical advantage" [Ref. 8: p. 288]. It includes movement to surprise an enemy, to maximize available firepower, mass for defense, or to enhance scouting efforts. In a littoral environment, maneuver of forces must include considerations of land based friendly and enemy forces. Maneuver can enhance friendly advantages or reduce those of the enemy. Ideally, both will occur.

C. SYSTEM WEAPON LOADS

Before analyzing the combatant missions under the principles listed in Section B above, a discussion of the probable weapon loads to be carried by the combatant vehicles is helpful. This section will provide a description of the payloads carried by the proposed wingships, the systems carried by current surface combatants, and a summary of the characteristics of the individual weapon systems.

1. Wingship Payloads

Surface combatant wingships are assumed to be capable of carrying modular weapons systems that allow the following loadings.

a. *Cruise Missile Carrier*

The cruise missile carrier is assumed to carry 32 Tomahawk Land Attack Missiles (TLAMs) or Tomahawk Ship Attack Missiles (TSAMs) and 32 Advanced Medium Range Air to Air Missiles (AMRAAMs) in a Mk-41 Vertical Launch System (VLS)

configuration. This is estimated to weigh 166 tons fully loaded.

b. NTACMS Carrier

The Naval Tactical Missile System (NTACMS) carrier aircraft is assumed to carry 32 NTACMS missiles and 32 AMRAAMs. The NTACMS missile is too large to fit into a VLS cell, so it will require a unique launcher, probably based on the one used by the Army. This new launch unit is estimated to weigh 166 tons fully loaded.

c. Mine Warfare Wingship

A wingship configured for the offensive mine warfare mission would carry up to 100 mines, each weighing 4000 pounds, and the associated storage and delivery equipment. A sensor suite will also be carried. These items are estimated to weigh 240 tons fully loaded.

A wingship configured for the mine countermeasure mission would carry a mine neutralization system similar to the SLQ-48. With its command and control system, this will weigh an estimated 55 tons.

d. Air Defense Wingship

These aircraft will be configured as radar wingships and missile wingships. The radar carriers will carry an Aegis-type phased array radar with a range of at least 500 kilometers. It will also carry 32 AMRAAMs for self defense. The missile carriers will contain 48 SM-2 Standard

surface to air missiles. The radar wingship payload is estimated to weigh 165 tons and the missile carrier payload is estimated to weigh 201 tons, fully loaded.

2. Current Surface Combatants

The primary surface combatants currently used to accomplish the four missions of interest (or similar ones) are described below.

a. Ticonderoga Class Cruisers

The Ticonderoga class cruisers displace between 9407 and 9590 tons fully loaded. They carry two Mk-41 Vertical Launch Systems, capable of holding up to 122 missiles. These can be SM-2 air defense missiles, Tomahawk cruise missiles, ASROC antisubmarine weapons, or a combination of these. Ticonderoga class cruisers also carry eight Harpoon anti-ship missiles in two quad launchers and two SH-60 Seahawk helicopters for early warning and anti-submarine missions. These cruisers utilize the Aegis fire control system. Ticonderoga class cruisers were used in the cruise missile attack role during Operation Desert Storm, and, in addition, have been used for fleet air defense missions.

b. Arleigh Burke Class Destroyers

The Arleigh Burke class destroyers displace approximately 9033 tons fully loaded. They also carry two Vertical Launch Systems and two Harpoon quad mounts. The missile load is similar to that of the Ticonderoga class

cruiser. Arleigh Burkes also utilize the Aegis fire control system. The primary missions of these destroyers are anti-air, anti-surface, and anti-submarine warfare. Later ships in the class are planned to have twin helicopter hangars for SH-60 Seahawks.

c. *Spruance Class Destroyers*

The Spruance class destroyers displace 8040 tons fully loaded. Being older ships, only 24 have the dual VLS systems for launching Tomahawks and ASROCs. The remaining ships carry 24 Sea Sparrow anti-aircraft missiles in Mk-29 launchers. Spruance class ships also mount two quad Harpoon launchers and two SH-60B helicopters. These destroyers are primarily used in the anti-submarine role, but the VLS equipped ships can conduct anti-surface missions as well.

d. *NTACMS Carriers*

The Navy currently has no ship executing the NTACMS mission. The Army uses the ATACMS missile launched from the M-270 Multiple Launch Rocket System. This is part of a larger Army artillery organization, and would normally be deployed as such.

The Navy uses five inch guns on many of its combatants for the shore bombardment mission. These guns have a range of only 12.8 miles, which is inadequate to support over-the-horizon littoral warfare. A recent Navy study of sea based bombardment requirements during a major regional

conflict concluded that 2500 guided 155mm rounds capable of reaching targets 75 miles inland would be needed. A similar NTACMS capability would be nearly as effective [Ref. 8].

e. *Mine Warfare Ships*

The Navy currently conducts minelaying operations with carrier and land based aircraft and submarines. No surface vessels are used to lay mines.

The Avenger and Osprey class ships are used to counter enemy mines replacing the aging Aggressive class ocean minesweepers, which are being retired. These new ships employ the SLQ-48 mine neutralization system and the SQQ-32 sonar.

SH-60 Seahawk helicopters are used by major combatant classes to search for mines in their vicinity. MH-53E helicopters also conduct aerial minesweeping with the Mk-105 towed sled. This sled uses a series of electrically powered buoyant cables dragging through the water, which simulates the magnetic characteristics of a surface ship. The signature then detonates any magnetic mines in the vicinity.

3. Weapon System Characteristics

The individual weapon systems characteristics are shown in Table I. These figures are assumed to be constant, regardless of the platform carrying them.

TABLE I: WEAPON SYSTEM CHARACTERISTICS

Weapon	Purpose	Range	Velocity	Warhead
TLAM	Land Attack	2500 km	885 km/hr	Nuclear
		1300 km	885 km/hr	Submun.
AMRAAM	Anti Air	40 km	Mach 4	150 kg HE
NTACMS	Land Attack	450 km	Mach 4.7	Submun.
Mines	Anti Ship, Anti Sub	0	0	See Table II
SM-2-IVA	Anti Air	>55 km	Mach 3	HE
TSAM	Anti Ship	450 km	885 km/hr	HE

TABLE II: MINE CHARACTERISTICS

Mine	Type	Length	Diameter	Weight	Charge
Mk-52	Bottom	2.89 m	844 mm	572 kg	270 kg
Mk-55	Bottom	2.89 m	1103 mm	996 kg	576 kg
Mk-56	Moored	3.50 m	1106 mm	1010 kg	159 kg
Mk-57	Moored	3.0 m	510 mm	934 kg	154 kg

D. TACTICAL COMPARISONS

This section contains an analysis of the tactical usefulness of the wingships compared to current methods. Qualitative and quantitative results (where appropriate) will show that wingships have significant tactical advantages in certain types of encounters.

1. Cruise Missile Carrier

The proposed wingships will be compared with conventional surface ships and carrier based aircraft in accomplishing the cruise missile attack mission.

a. *Common Methods*

In order to conduct a cruise missile attack, conventional ships, carrier launched aircraft and wingships must execute the same basic functions. They will differ by the speed with which the attack is presented, the threats to which the attackers are exposed, and the number of missiles carried.

Prior to executing an attack, the target must be identified and processed into an attack plan, the firing platforms must move into cruise missile range (if not there already), and finally the missiles or attack aircraft must be launched.

The design mission assumes that national reconnaissance assets detect the rollout of enemy ballistic missiles. Since the wingships carry the same launch system

and processors as the surface ships, there will be no difference in the capability of wingships and conventional methods to detect and plan an attack. Movement and firing of the missiles will vary among the methods. Figure 7 shows the Tomahawk range coverage for launchers in the Persian Gulf.

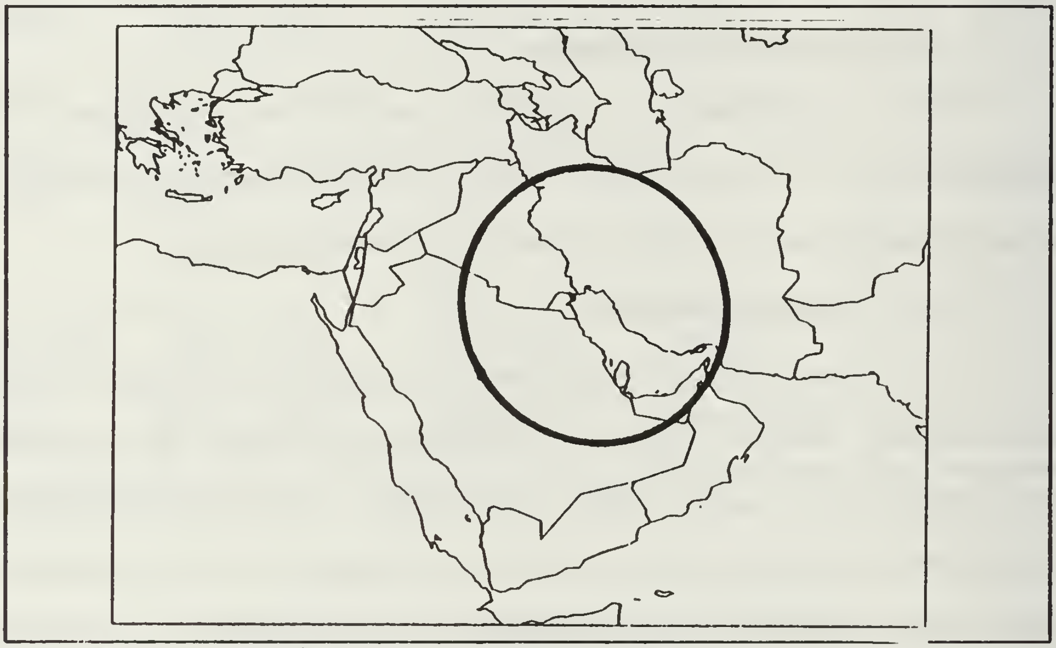

Figure 7: Persian Gulf Tomahawk Range

b. Conventional Ships

If the ships are on station in the theater of operations, there should not be any time required to move into Tomahawk range (1300 km). If this is not the case, or the targets are significantly inland (Baghdad, for example, is 620 km from the north end of the Persian Gulf; Northern Iran is nearly 1300 km from the Gulf), the ship would have to move closer before launch. Today's ships travel at approximately

32 knots (59.3 km/hr), and a Tomahawk missile cruises at roughly 885 km/hr. The surface ship must therefore be positioned so that the missile can fly the distance within the one hour set-up time of a Scud or Scaleboard missile, allowing for the time required for detection and mission planning. With an optimistic 15 minute delay, the ship must be stationed no farther than approximately 663 km from the target.

Against a fixed target, the time is not as critical. The crucial time parameter in this case is the time spent inside the effective range of the enemy's weapons. Every hour spent inside this range increases the chance of an enemy attack. Assuming a distance of 500 km to the necessary launch point, a surface group will spend approximately 8.43 hours inbound and outbound, giving the enemy 8.43 hours to possibly launch an effective first strike. The battle staff must therefore plan to eliminate or neutralize the enemy's striking power in addition to attacking the designated target. This may require additional ships that could have been attacking other targets, or could divert missiles from the primary target to service the threat.

Conventional ships face threats from enemy ships, surface to surface missiles, aircraft, mines, or torpedoes. A speed of 32 knots may outrun a torpedo if it is detected far enough away, but would not be fast enough to evade any of the other threats.

c. Carrier Based Aircraft

In a dash, carrier based attack aircraft can approach the speed of a Tomahawk missile. Given the high value of a carrier battle group, the carrier will certainly be located beyond the range of any enemy shore based defenses. A major advantage of a carrier based force is the ability to launch aircraft to patrol an area close to prospective launcher sites. A disadvantage is the need to maintain continuous coverage, which burns fuel and wears out aircraft and aircrews. Anti-air threats must be neutralized for the duration of the patrols. This can be done with other carrier based aircraft, or with missiles.

Today's carrier battle groups consist of one or more aircraft carriers and a mixture of frigates, destroyers, and cruisers, which can carry Tomahawks. This configuration is the same as that of a non-carrier group, but with the addition of the high-value carrier. Since carriers are very scarce assets, they would probably be needed to support forces in contact ashore.

d. Wingships

A cruise missile carrier wingship would accomplish the mission in a manner similar to that of the surface ship. The major difference is in the time spent within the range of enemy weapons. A wingship traveling at 400 knots (741 km/hr) would spend only 40.5 minutes closing a 500 km distance,

versus 8.43 hours for a conventional ship. The speed advantage of the wingship is obvious in this case.

A wingship will be exposed to different threats from a conventional ship. These aircraft will be susceptible to attack from anti-aircraft weapons, anti-surface weapons, and torpedoes while stationary or moving at low speeds, and only anti-aircraft weapons while at cruising velocity.

A wingship resembles a large transport aircraft structurally, as opposed to a surface ship. The wingship will be far less armored, and far more vulnerable if hit by an enemy weapon. Surface ships may be able to withstand one or more missile impacts, but a wingship probably would not. It would rely on its speed to prevent engagement by the larger surface to surface missiles.

e. Conclusion

Tactically, the wingship and conventional ship are equivalently capable of executing the rapid reaction Medium Range Ballistic Missile (MRBM) neutralization mission. The short set-up times needed before a Scud or Scaleboard launch demand that any ship be well within Tomahawk range in order to possibly attack the missiles before launch. A carrier based air unit could be based at a much farther distance, with continuous air patrols near prospective missile sites.

The speed advantage of the wingship becomes most apparent in missions that require a closure over a distance

covered by enemy weapons. The wingship travels an order of magnitude faster than a conventional ship, which significantly reduces a wingship's susceptibility to the enemy's defenses.

2. NTACMS Carrier

a. Common Methods

In order to conduct a shore bombardment mission, any friendly platform must perform the same basic tasks. The target must be identified and the mission must be planned. In the case of mobile targets (such as an enemy armored force moving into a friendly nation) their location at the time of attack must be predicted. This requires a detailed analysis of the battlefield and sensors to track the target's movements.

Once the mission is planned, the firing platform must move into bombardment range. Since tactical bombardment weapons have considerably less range than most threat aircraft and anti-ship missiles, any such threats must be neutralized. Any sea based launcher will necessarily spend the entire mission within threat range.

Finally, at the designated time and place, the attacker launches his attack. The enemy may possess counter-battery radars, which can locate the launch points of artillery or rocket rounds. To avoid counterbattery fire and reduce the effect of dedicated antiship defenses, the firing platform would move after one (or a few) launches.

b. *Conventional Ships*

Most current combatant ships carry the Mk-45 five inch gun system for possible shore bombardment missions. This gun only has a 12.8 mile range, so it can only attack targets relatively close to the shore. This may be adequate for the initial phases of an opposed amphibious landing, but these weapons cannot accomplish the rapid destruction of a massed armored force at any significant range inland.

The Iowa class battleships were capable of conducting a deep bombardment, but these ships are no longer in service. Their 16 inch guns could deliver a 2700 pound warhead 23 miles [Ref. 10: p. 717].

c. *Carrier Based Aircraft*

Carrier based attack aircraft can attack massed armored targets at a considerable distance inland. Since carrier based aircraft are a scarce commodity, the planning for their use in this mission must include considerations for their need elsewhere. Carriers are usually a significant distance offshore, so the time delay between identifying the target and actually attacking it will be longer than for other methods.

Manned aircraft experience additional threats when conducting interdiction strikes. All anti-aircraft weapons in and around the target, and along the ingress and egress routes, will threaten the aircraft. Doctrine requires

integration of air defense assets into movement formations, so any enemy force worth attacking will probably be well defended.

d. Land Based Aircraft

Land based fixed wing aircraft suffer the same problems listed in Section 2(c) above. In addition, friendly bases may not be available, depending on the theater of conflict.

Strategic bombers can accomplish this mission from bases in CONUS or other locations distant from the target. If on alert, they may be the fastest choice. Their major drawback is their very limited numbers, and the high threat environment into which they would have to fly without escort. This would be a very risky method.

Rotary winged aircraft may be available if Marine or Army units are already engaged, or are nearby. In most cases, attack helicopters are used to support forces in direct contact with the enemy, or enemy tactical reserves just behind the front lines. Helicopters have a limited range, which also limits their usefulness against deeper targets.

e. Wingships

A wingship carrying NTACMS missiles can stand offshore and attack targets up to 160 km away. Each NTACMS can carry 13 anti-armor submunitions, and each wingship can carry 32 missiles.

A major advantage of a wingship in this role, in contrast to a surface ship carrying NTACMS, is the rapid maneuverability available to the wingship. These aircraft can rapidly move to NTACMS range to attack an enemy in a different location, or to attack different echelons of the same main enemy formation before they can reconfigure into a less vulnerable formation.

In the event of a sudden outbreak of hostilities, a wingship can move to the vicinity of the invasion much quicker than a surface force. This allows an earlier attack against the enemy, buying time for defenders to prepare to repel them. Figure 8 shows the distance an enemy force could move as a function of friendly force deployment speed.

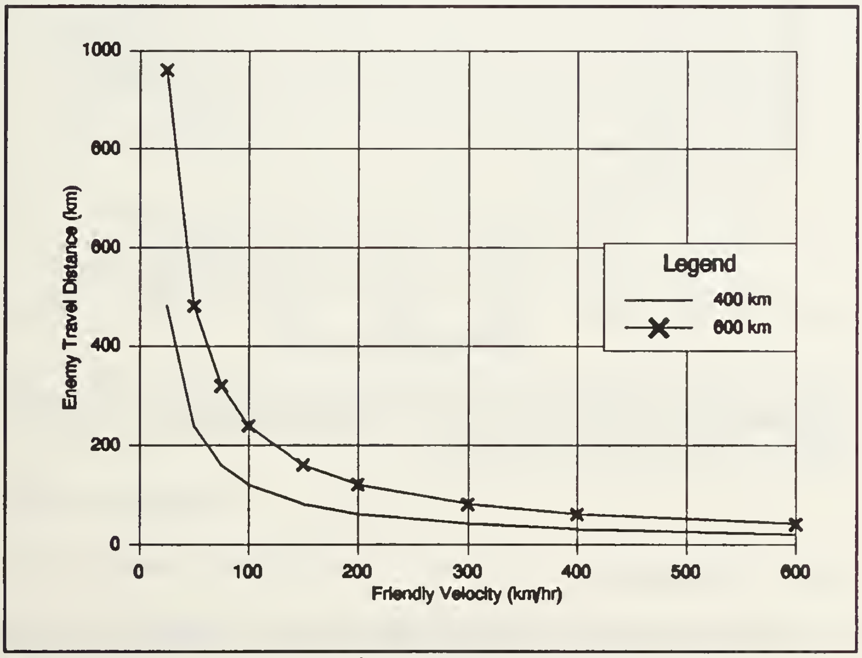

Figure 8: Enemy Distance Traveled vs Friendly Deployment Speed

Wingships are susceptible to the same threats listed in section (c) above. Since the aircraft must fire its missiles from positions much closer to the target than required for a cruise missile attack, shorter ranged anti-ship weapons would be a factor. Any threat must be suppressed prior to, or in conjunction with, the strikes against the interdiction target. Figure 9 shows the time a friendly unit spends exposed to enemy weapons as a function of the friendly unit's speed.

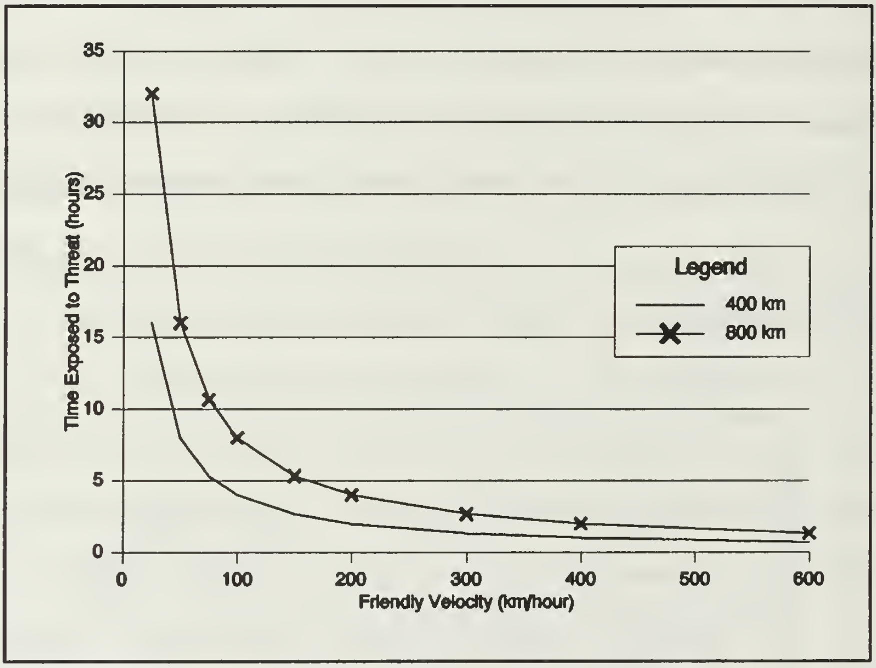

Figure 9: Friendly Unit Time Exposed to Enemy Weapons vs Speed

f. Conclusion

Wingships carrying the NTACMS missile can effectively conduct deep interdiction missions against enemy

ground forces. The wingship's mobility advantage and reduced susceptibility to land based anti-aircraft weapons enhances its usefulness. Land or carrier based aircraft require riskier approaches through hostile territory, but they offer nearly identical strategic reaction time if located within their respective combat radii. The effectiveness of deployment time is shown in Figure 10, where effectiveness is measured as number of anti-armor munitions deliverable versus time to deploy.

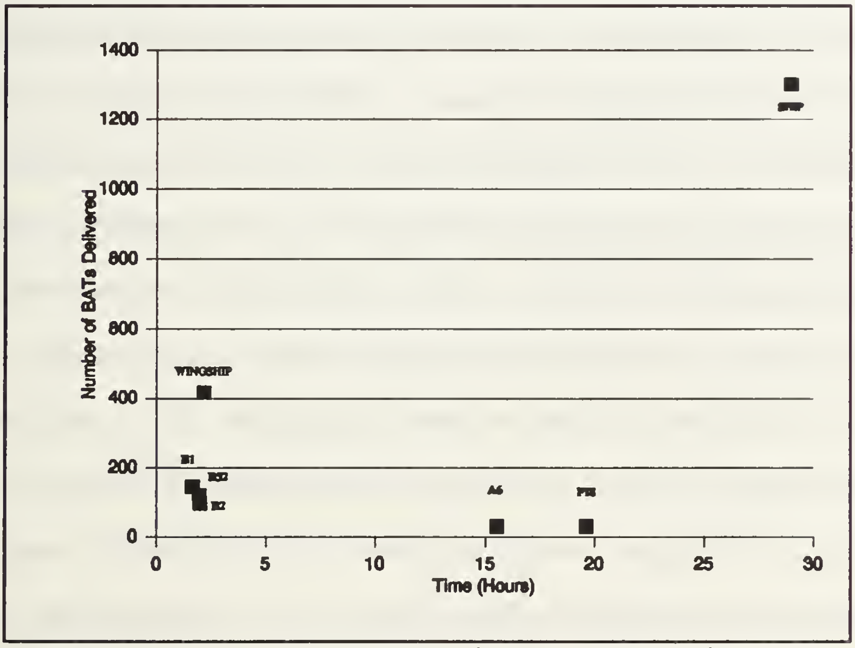

Figure 10: Ordnance Delivery Effectiveness

3. Mine Warfare

a. Common Methods

In order to conduct offensive or defensive mine warfare, any ship or wingship must first get to the location

of interest, and remain there throughout the duration of the mission. A minelayer must accurately deploy its mines in the proper patterns, and a mine countermeasures ship must find the enemy mines and then neutralize them.

b. Current Minelayers

Today's Navy uses submarines and aircraft to lay mines. Sturgeon and Los Angeles class attack submarines can carry the Mk-60 Captor mine and the Mk-67 Mobile mine. Submarines have the advantage of stealth during operations, and are susceptible only to anti-submarine weapons (while submerged). Against a littoral enemy, subs can easily hide if detected while laying mines. Disadvantages to submarine minelaying are the limited number of mines carried, and the speed with which they can transit to the target location and stealthily emplace mines. If a minefield is needed quickly, a submarine may not be able to get there in time.

Aircraft have the ability to rapidly lay a minefield, but lose the covert emplacement capability of a submarine. Carrier based aircraft can rapidly lay mines if the carrier is located close enough to the target location. B-52 bombers can also airdrop mines, with an intercontinental transit range capability.

Aircraft cannot emplace mines as accurately as a submarine, due to the inherent errors associated with an air drop. They must fly slowly during the drop, and are therefore

more susceptible to enemy air defenses. Fighter escorts would certainly be required.

c. Wingship Minelayers

The proposed mine load for the wingship is 100 4000 pound mines. This is slightly more than the loads carried by strategic bombers. Navy aircraft carry far fewer mines (a P-3 carries six Mk-55/56 mines, and an A6-E carries twelve). One wingship can carry as many mines as 8 1/3 A6's.

While en route transit time for wingships will be comparable to those of strategic bombers, a wingship can slow down to place the mines much more accurately than a faster bomber delivery, and the lower flight altitude aids in wingship delivery accuracy. Wingships will be slightly less susceptible to anti-air weapons since they fly much lower than most conventional aircraft, which reduces the range at which enemy radars can detect them. Fighter escort will be desirable for both wingships and conventional aircraft.

The wingship also offers added flexibility over conventional aircraft. Its sea-sitting capability allows the wingship to remain on station if political or operational needs require a delay in minefield emplacement. Submarines can also loiter in the area, and are not as easy to detect as a wingship on the surface.

Wingships combine the speed and mine carrying capability of strategic bomber aircraft with the flexibility

and accuracy of submarine minelayers. They provide the ability to rapidly emplace a precise minefield without the need to be near the target prior to being ordered to execute the mission. In a rapidly developing situation, the speed and flexibility of the wingship provide a capability not present in today's force.

d. Current Mine Countermeasures

Avenger and Osprey class vessels are used to conduct mine countermeasures missions. MH-53 helicopters towing the Mk-105 also are used to clear mines. Only 14 Avengers and 10 Ospreys are in service, along with three aging Aggressive class ocean minesweepers, which are being retired.

Surface vessel minesweepers rely on sonar and the SLQ-48 mine neutralization system to defeat mines. Guns on ships and SH-60 helicopters are also used to detonate any mines visually identified.

e. Wingship Minesweepers

A wingship in the mine countermeasure mission would search for and destroy mines in advance of a surface group. The speed of the wingship allows it to cover a larger area than a surface ship, and it can remain on station longer than a helicopter. The main limitation will be the operational speed of the SLQ-48 system, which is independent of the launching platform. The metal fuselage and wings of the wingship would create a signature that could detonate

enemy mines, while the wooden hulls of the Avengers and plastic hulls of the Ospreys make them less susceptible. The aircraft-style construction of a wingship fuselage would make it much more vulnerable in the event of a detonation.

If a slow speed power augmented ram profile is used to tow a mine clearing sled, the fuselage would largely be out of the water, allowing the sled to detonate the mine. Power augmented ram (PAR) mode requires much more fuel than normal in ground-effect cruise, so the mission duration in this profile would be shorter.

The wingship can be effective if the mission calls for mine clearing at a location not currently patrolled by a surface mine warfare ship. For example, discovery of mines in a commercial shipping route could require rapid deployment of mineclearing assets. As shown in Section 5 below, a wingship can deploy much faster to an evolving crisis location.

The primary advantage of wingships over surface mine clearing ships is a faster deployment and repositioning capability. With only two SLQ-48 systems, a wingship would have identical clearing capacity as an Avenger class minesweeper. Additional airborne sensors and expendable ordnance that would be effective at wingship cruise speeds would greatly enhance their usefulness in mine warfare missions.

4. Air Defense

a. Common Methods

In order to provide an effective air defense umbrella over a land or sea force, a unit must first identify the probable enemy air avenues of approach, and must position early warning radars and air defense weapons to attack aircraft using these routes. With the proliferation of stand-off weapons, early identification and attack are necessary to destroy the carrier aircraft before it can release its stand-off weapons.

It is assumed that the mission of interest involves air avenues of approach over water or coastal areas within range of current naval anti-aircraft weapons. Possible targets to be defended include ports, disembarking troops or supplies, other coastal facilities (airfields, oil terminals, etc), or combatant or non combatant ships at sea. Fixed targets can be defended on a "point" basis or "area" basis. Point air defense requires assets to be deployed to defeat a threat expected to attack that target. Area air defense provides an umbrella of coverage over a wide area that includes the high value target. Mobile assets (ships at sea, moving ground forces) require the area coverage technique.

b. Aegis Air Defense

Ticonderoga and Arleigh Burke class warships carry the Aegis air defense system, with the SPY-1B phased array

radar and SM-2 series missiles for area air defense coverage. This system is effective to a range of approximately 460 km for air search, and 73 km for the missiles. The Aegis command and control system integrates the weapons of all the ships in the task force, allowing prioritization of fires and the prevention of multiple (overkill) engagements. Ships carrying the surface- to-air missiles are usually found on the outer edges of a task force formation to protect the assets in the middle.

Early warning and targeting is provided by the SPY-1B radar and long range warning comes from aircraft such as the E-3 AWACS and E-2 Hawkeye. Their radars have ranges of over 370 km. The Aegis radar is effective up to approximately 460 km. The information on incoming aircraft or missiles is passed to the missile launch ships, which engage the targets when they become in range.

c. Land Based Air Defense

High priority shore facilities as well as vessels at sea can be covered by ground based air defenses. The Patriot missile system provides area air defense coverage to a range of approximately 70 km, and the Hawk system can provide coverage to roughly 40 km. The Patriot can also provide point defense against tactical ballistic missiles, as demonstrated during Operation Desert Storm.

Land based air defense units are limited in mobility. Although over-the-road speeds are faster than surface ship cruising speeds, ground based systems have a significant tear down and set up time. During the entire period, they cannot engage targets. Also, these systems must be deployed by air or sea to the theater, which can take weeks, and require either a friendly port and host nation or a mature force in-theater. Ground based systems are an excellent choice for defending stationary high value locations, if adequate deployment and setup times are available.

d. Wingships

The design air defense mission envisions radar wingships mounting an Aegis-equivalent radar system and another wingship carrying the missiles. Once in the sector to be covered, this arrangement would have an equivalent capability as the current Aegis configuration. Again, the major advantage of the wingship is its deployment speed.

Wingships can provide air defense coverage in advance of a surface group or aerial operation before the surface ship or land based air defense systems can be operational. This can be in conjunction with the deployment of carrier or land based aircraft to also defend against air attacks.

Wingships can also reposition to counter an incoming threat. If enemy bombers are detected far enough away, a wingship can move at its 400 knot cruise speed to rapidly close the distance and launch missiles before the bombers can launch theirs. This tactic would not work against faster targets, but it can be used to offset the flexibility in ingress routes available to a long range bomber.

5. Strategic and Operational Considerations

The above sections show that the wingship's major tactical advantage lies in its ability to rapidly move from a base or port to the mission location and remain there for a relatively long period of time. This section will discuss the deployment and logistical consideration of wingship utilization.

a. Deployment

A wingship's cruising speed of 400 knots puts the entire world only hours away from CONUS home ports. Table III shows the distances between several port locations and strategic overseas locations, and the transit times for vessels moving at 30 and 400 knots.

TABLE III: STRATEGIC DISTANCES

From	To	Distance (Miles)	Travel Time (30 knots)	Travel Time (400 knots)
Norfolk	Gibraltar	3973	115.1 hrs	8.63 hrs
	Cape Town	7946	231.8 hrs	17.26 hrs
	Panama Canal	2217	64.2 hrs	4.82 hrs
	Strait of Hormuz	13638	395.0 hrs	29.63 hrs
	Israel	6376	184.7 hrs	13.85 hrs
San Diego	Tokyo	5747	166.5 hrs	12.49 hrs
	Honolulu	2643	76.6 hrs	5.74 hrs
	N. Korea	8002	231.8 hrs	17.38 hrs
Honolulu	N. Korea	5359	155.2 hrs	11.64 hrs
	Manila	5452	157.9 hrs	11.84 hrs
	Taiwan	5230	151.5 hrs	11.36 hrs

Table III shows that wingship response can be measured in hours, versus days for surface ships. Figure 11 shows a world map with this information presented graphically.

Figure 11: Strategic Deployment Schematic

Over the more extreme ranges, the wingship will have to refuel. The baseline configuration has a nominal range of 5400 miles. This will require access to either a friendly facility at an appropriate location, or prepositioned fuel ships. Alternately, a wingship tanker could refuel itself and others in the open sea. Regardless of the method, any deployment longer than 5400 miles will require additional time to conduct refueling operations. This range is a function of the wingship design. Using the parametric relationships of Reference 10, Figure 12 shows the range versus the aspect ratio and wing loading.

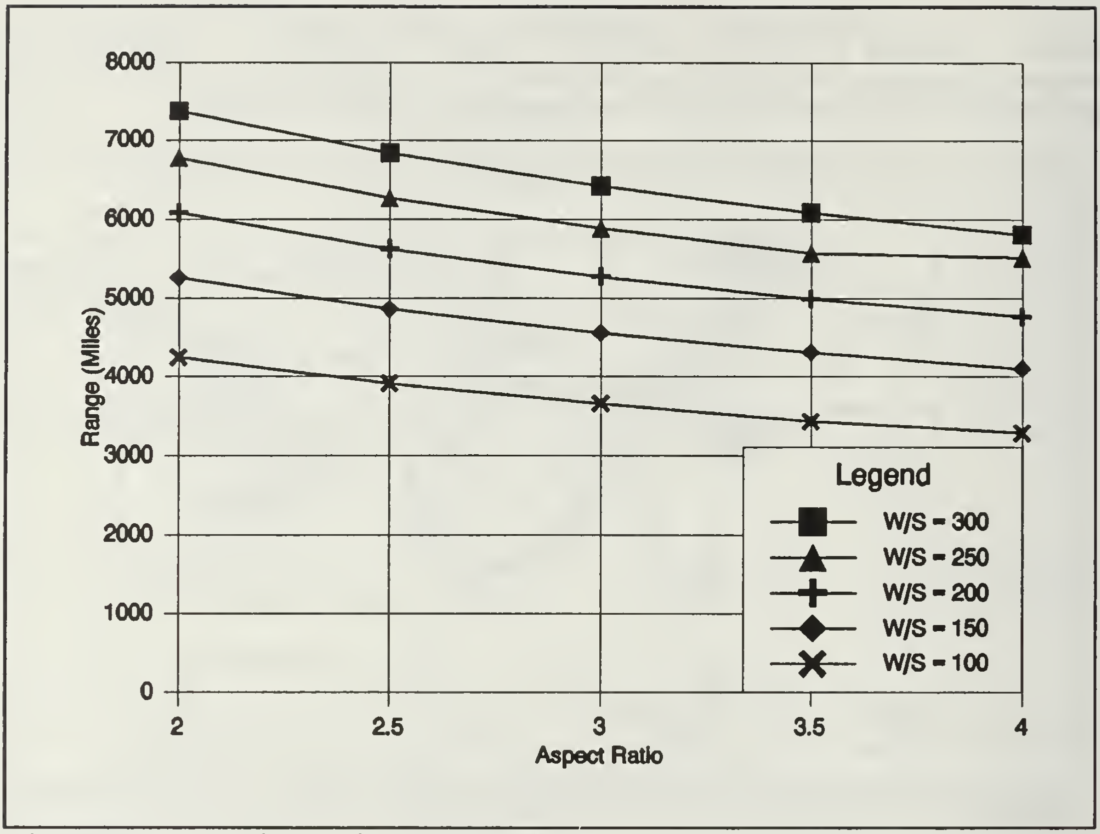

Figure 12: Wingship Range Map

b. Logistics

As a revolutionary form of aircraft, a wingship will have unique logistical requirements. As covered in paragraph 5(a) above, wingships will require large quantities of jet fuel. Qualitatively, a wingship force will need access to jet fuel tankers. Aircraft carriers carry jet fuel for their embarked aircraft, but a wingship's needs will deplete this amount relatively quickly. Additional capacity will be required in the form of dedicated jet fuel tankers for extended wingship operations.

Wingships may also need unique port and handling equipment support. As shown in Figure 1, the wingspan of the baseline wingship is 141 feet, while a Ticonderoga class cruiser is 55 feet wide, and a Nimitz class aircraft carrier is 134 feet wide. The wingship may need a special dock facility due to its overall width if one designed for an aircraft carrier is not available.

If the wingship is designed to operate from water, it cannot be pulled ashore for overhauls or major repairs without special equipment. With weights in the 1000 ton class, modifications for ground handling would require a much heavier structure, due to the presence of gravity loads not balanced by water (buoyant) loads. To avoid this weight penalty, the wingship should be designed for maintenance afloat. Special drydock facilities would be necessary for work requiring the wingship to be out of the water. An example is fuselage inspection or repair.

E. CONCLUSION

This chapter has shown that the wingship is tactically capable of accomplishing the four defined design missions. Current assets can perform similar missions, but without the deployment speed and flexibility of the wingship. The next chapter will consider the technical considerations of wingship employment.

IV. TECHNICAL CONSIDERATIONS

Wingships behave as aircraft during portions of their missions, and as ships during other segments. As a hybrid vehicle, the wingship must meet requirements for satisfactory performance in both environments, as well as during the transition between them (takeoffs and landings). Flight in-ground-effect presents its own special circumstances that affect the operational usefulness of the system. This chapter will cover the effects of sea waves on wingship cruise performance, sea-sitting performance, and the impact of the numerous takeoffs and landings required during typical missions.

A. EFFECTS OF SEA STATE

The sea state is a numerical representation of the intensity of ocean waves, as measured by the expected wave crest heights. This must be considered when designing a wingship. The designer must consider tradeoffs between the aerodynamic efficiency of a lower cruise altitude and the possibility of hitting a wave. At 400 knots, a wave impact could be catastrophic.

1. Sea State Definitions

Current design practice characterizes sea states as follows [Ref. 12: p.48]:

TABLE IV: SEA STATE DEFINITIONS

Sea State	Significant Wave Height
0-1	10.66 ft
2	1.0 ft
3	3.0 ft
4	6.17 ft
6	10.66 ft
6	16.40 ft
4	24.61 ft
8	37.73 ft
>8	>45.93 ft

The significant wave height is called $H_{1/3}$. $H_{1/1000}$ and $H_{1/10,000}$ denote the amplitudes of the "one in a thousand" and "one in ten thousand" highest waves.

The distribution of waves for a given sea state is assumed to follow a Rayleigh distribution, with $H_{1/1000} = 1.925xH_{1/3}$ and $H_{1/10000} = 2.22\ H_{1/3}$. The Rayleigh distribution in itself allows a small possibility of very large waves. For design purposes, these are usually ignored [Ref. 13: p.11].

Figure 13 shows a summary of the probability of encountering the various sea states. This is a year round average for both the North Atlantic Ocean and world wide conditions. The vertical axis shows the percentage of time that the localized significant wave height will exceed that shown on the horizontal axis. For example, a $H_{1/3}$ of 12 feet will be exceeded 10% of the time, or conversely, 90% of the time the significant wave height will be less than 12 feet.

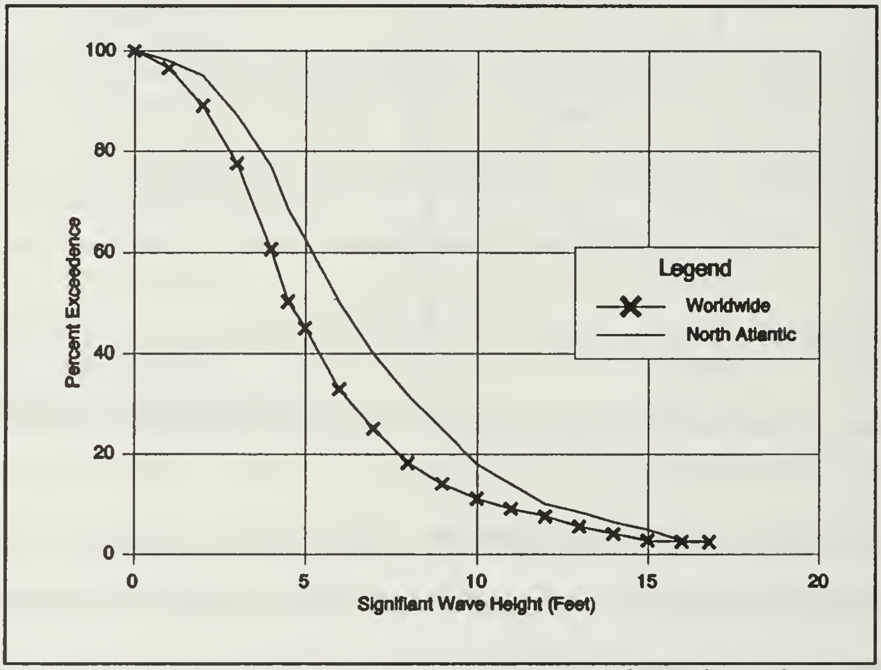

Figure 13: Expected Sea State Distribution

2. Cruise Performance

Today's wingship designers use this information to determine the aircraft's height above the water during cruise flight. Experiments have shown [Ref. 13] that safe flight occurs when the wing endplate bottoms remain above the $H_{1/3}$

significant wave height, and the bottom of the wing stays above the largest expected wave ($H_{1/1000}$). The designer chooses a design sea state, and sizes the vehicle according to the wave heights for that state.

The waves themselves do not affect the cruise performance of the wingship [Ref. 14: p.12], but the mean cruising height does. Figure 14 shows the effect of height above the ground plane (non-dimensionalized to chord length) on the effective aspect ratio of a wing, which is the aspect ratio used for performance calculations. This is a measure of aerodynamic efficiency, since

$$\frac{L}{D}=\frac{C_L}{C_D}=\frac{C_L}{C_{D_o}+\dfrac{C_L^2}{\pi e AR_{eff}}} \tag{7}$$

A higher aspect ratio results in a lower drag coefficient, which improves the ratio of lift to drag. From an efficiency stand point, the designer wants the wingship to fly as low to the ground as possible.

These two requirements are clearly contradictory. The design sea state must be chosen carefully, assessing the likely locations for employment and not over designing the aircraft. A wingship design that is too risky due to an underestimated maximum sea state requires excessive power margins to lift the craft over a large wave, or risks a catastrophic wing impact with the water.

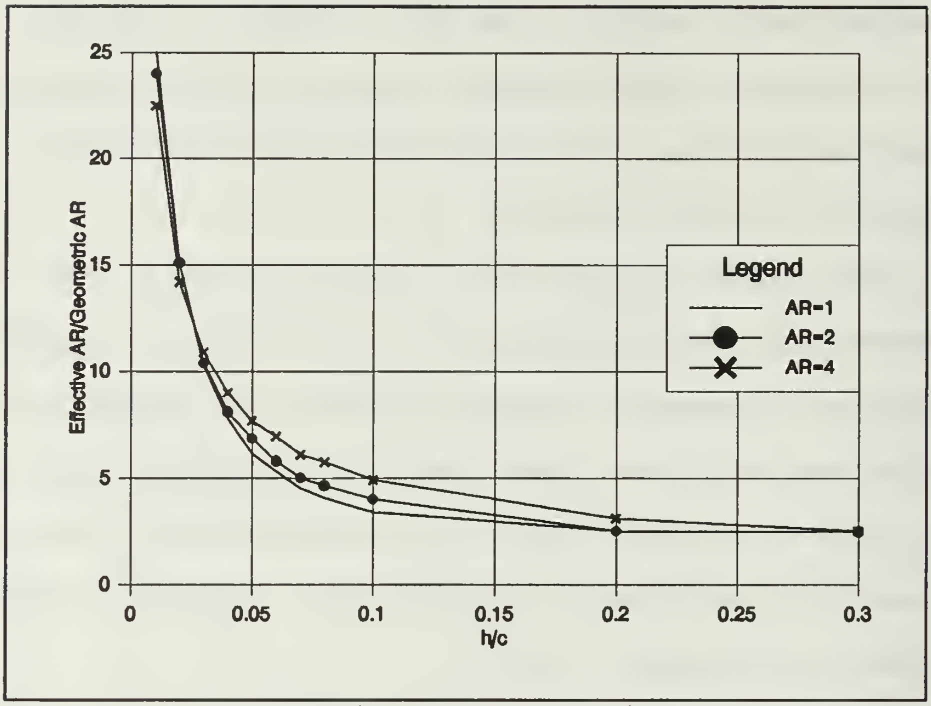

Figure 14: Effective Aspect Ratio Versus Height Above Ground Plane

The tactical implication of this tradeoff involves the engine thrust and fuel margins designed into the wingship. If the wingship is designed for an overly high sea state, the thrust available will exceed that required most of the time, reducing engine efficiency. The aircraft can fly lower to take advantage of the better aerodynamic efficiency at the lower height, but then the engines will be operating away from their optimum design point. Conversely, if the wingship encounters sea states higher than the design sea state, additional thrust beyond the optimum cruise setting will be required. Both situations reduce the total range of the wingship for a given fuel load. Figure 15 shows this graphically. The mission planner must consider the sea

conditions en route to the target and adjust refueling points as necessary.

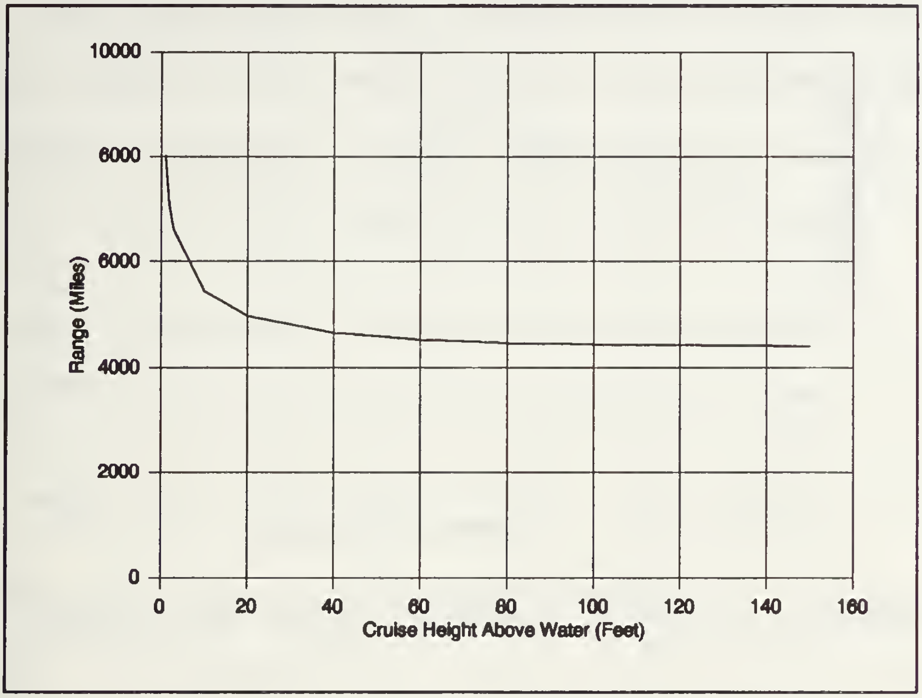

Figure 15: Range Versus Cruising Height

3. Takeoff and Landing

Increasing sea state wave height creates additional hydrodynamic drag on the vehicle during takeoff. This is manifested by a decrease in acceleration and an increased distance required to leave the water. Figure 16 shows the takeoff distance as a function of $H_{1/3}$. This data is from Reference 15, which contains a parametric study of a wingship in the same 1000 ton weight class as the hypothetical combatant wingship. The reduced acceleration for this example vehicle is shown in Figure 17. Assuming a specific fuel consumption of 0.681 lb/hr/lb, the fuel required for these

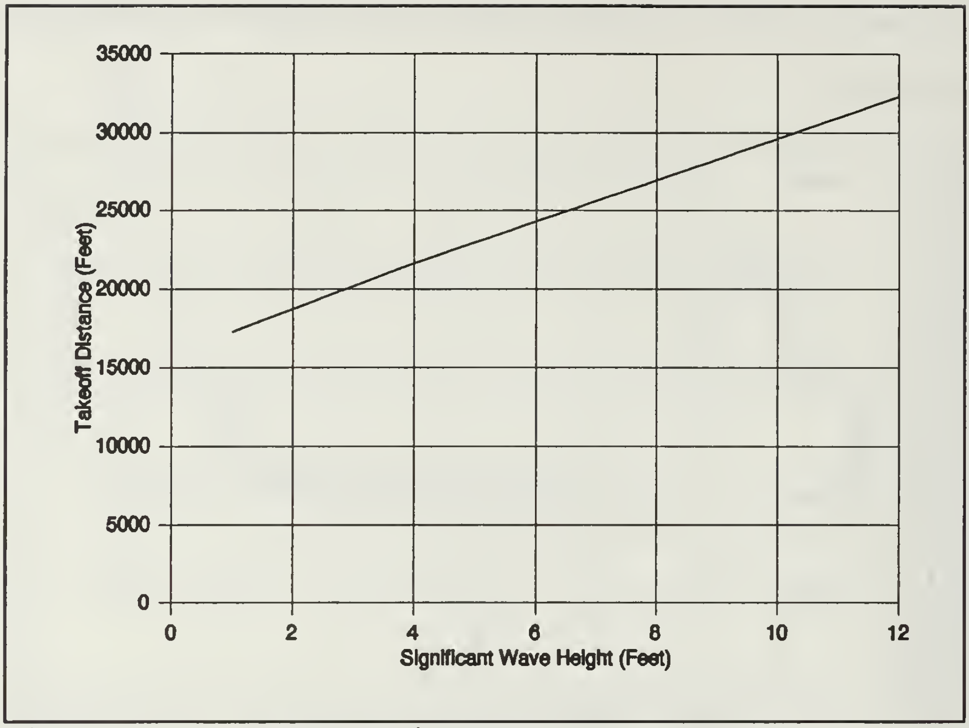

Figure 16: Takeoff Distance Versus Sea State

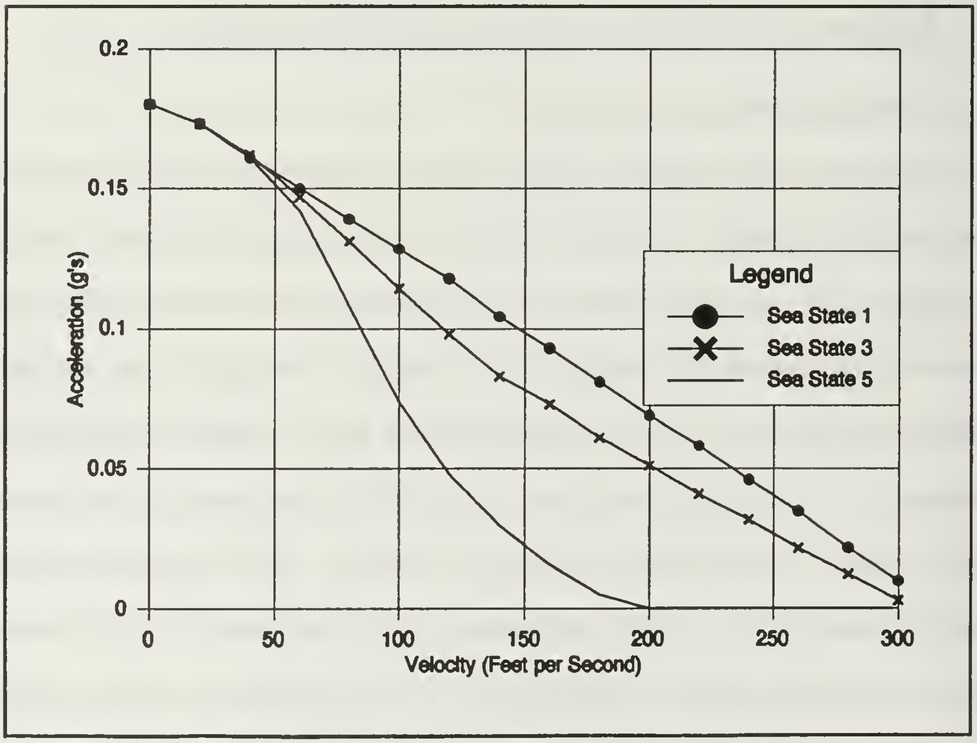

Figure 17: Takeoff Acceleration, 200 kt Takeoff Velocity

takeoffs is shown in Figure 18. As a comparison, the General Electric CFG-50A engine, with a maximum thrust of 49000 pounds, has a specific fuel consumption at cruise of 0.654 lb/hr/lb. [Ref. 16: p. 14-6] These calculations assume a 200 knot takeoff velocity. This velocity for a wingship is defined as that velocity where the entire vehicle has left the water.

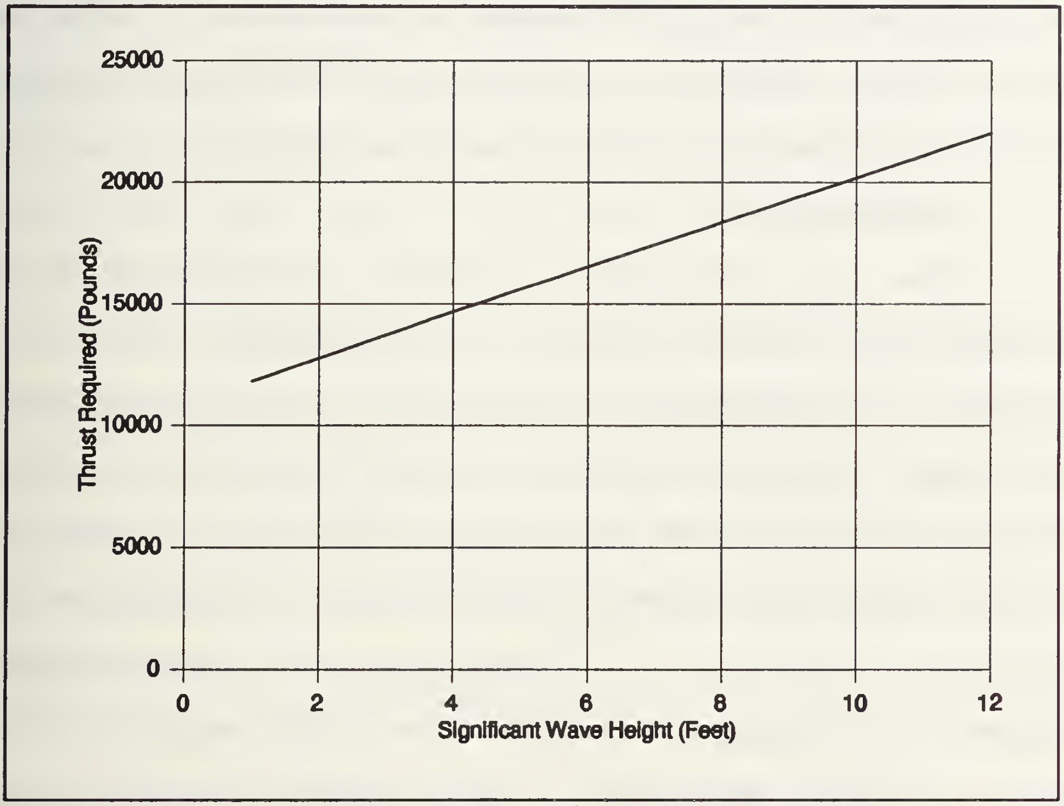

Figure 18: Takeoff Fuel Required

Figure 17 shows that a wingship designed for a certain sea state must have a sufficient thrust margin to allow a takeoff in seas other than those for which it was designed. If the sea state requires too much thrust, the wingship will not be able to take-off. This could become a problem if the

wingship is designed for a low sea state and finds itself in a severe storm. The allowable operating envelopes for the aircraft must include procedures for moving before potentially crippling storms arrive.

This creates a significant difference between surface ship and wingship operations. A surface ship can operate in all but the most severe conditions (such as hurricanes), but a wingship would have more restrictive operating limitations. During stormy seasons, wingships may not be suitable for operations in certain storm-prone locations.

4. Conclusion

The sea environment presents challenges to the wingship that are not issues for conventional aircraft or ships. The performance of a wingship is strongly dependent on the height above the water at which it flies, which is directly related to the sea state. Similarly, the fuel and distance required to take off from a rough sea is greater than that from a smooth sea. In operations that require repeated takeoffs and landings, this difference can seriously affect overall mission endurance. Very severe sea states can completely preclude a wingship from operating, which limits its usefulness.

B. SEA SITTING

The portion of a wingship's mission that occurs afloat on the sea surface is called sea sitting. In this environment,

the wingship behaves exactly like a ship. This section will discuss the effects of the sea environment on the wingship while on the surface.

1. Introduction

While sitting on the sea, a wingship's motion is governed by the rules for ship stability. Wave heights and frequencies will cause rolling and pitching movements which can affect the vessel's suitability as a weapons launch platform. Sea stability must be considered by the wingship designer to ensure that the aircraft will remain upright in heavy seas, and that it will not exceed weapons launch parameters.

The ocean provides a buoyant force which keeps a body afloat. This force acts upon the entirety of the submerged portion of the ship. A conventional aircraft is supported on the ground by its landing gear. A major structural concern for a wingship is the variable nature of the buoyant force in unsteady seas.

Finally, this section will consider the effects of the constant direct exposure of the aircraft to the corrosive ocean water and associated spray. All wingship systems must be designed with sea water exposure in mind.

2. Stability

Sea stability characterizes the motion of a floating object when perturbed by an outside force. In simple terms,

stability deals with a vessel's tendency to remain in an upright position while in unsteady seas. A ship's stability is a function of its geometry, load condition (center of gravity location and draft) and sea state. The geometry involved is shown in Figure 19 [Ref. 17: p. 2].

The primary factor affecting the stability of the ship is the distance between the center of gravity and the metacenter. The metacenter is a hypothetical point above the buoyant center, through which the buoyant forces act when the vessel is inclined. As the distance between the metacenter and the center of gravity increases, the vehicle becomes more stable.

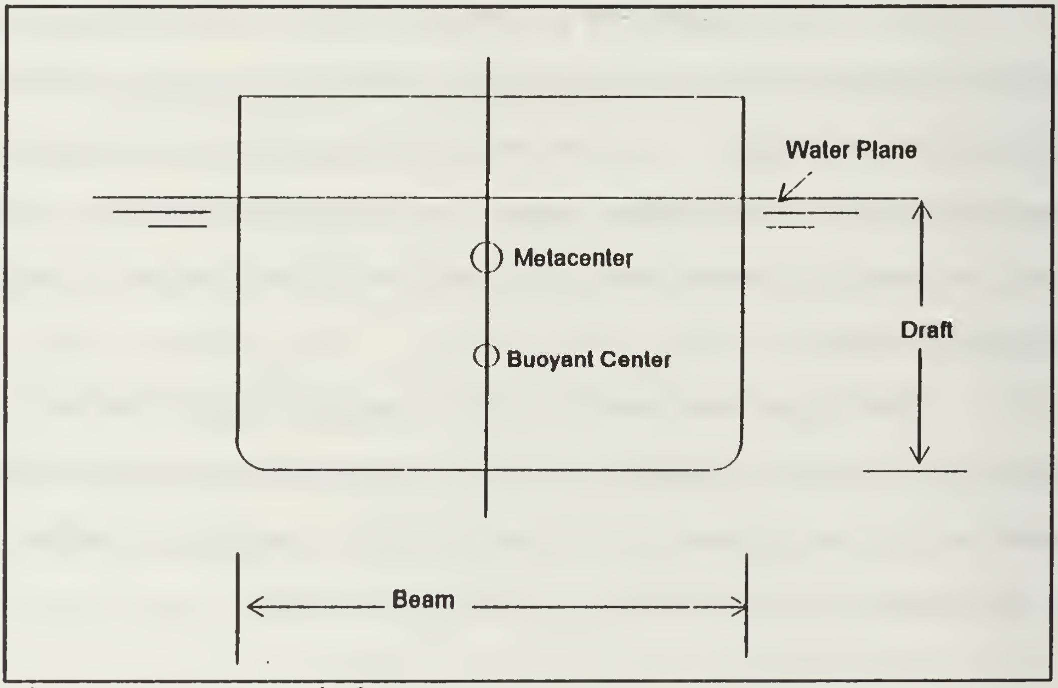

Figure 19: Stability Geometry

If the vessel changes its loading condition (by firing missiles, for example), the location of the center of gravity

will change, so its sea stability will also change. The designer must account for this shift when placing the wingship's weapons.

Figure 20 shows diagrams of a stable, a neutrally stable, and an unstable ship. Note that the position of the center of gravity with respect to the metacenter determines the stability of the ship.

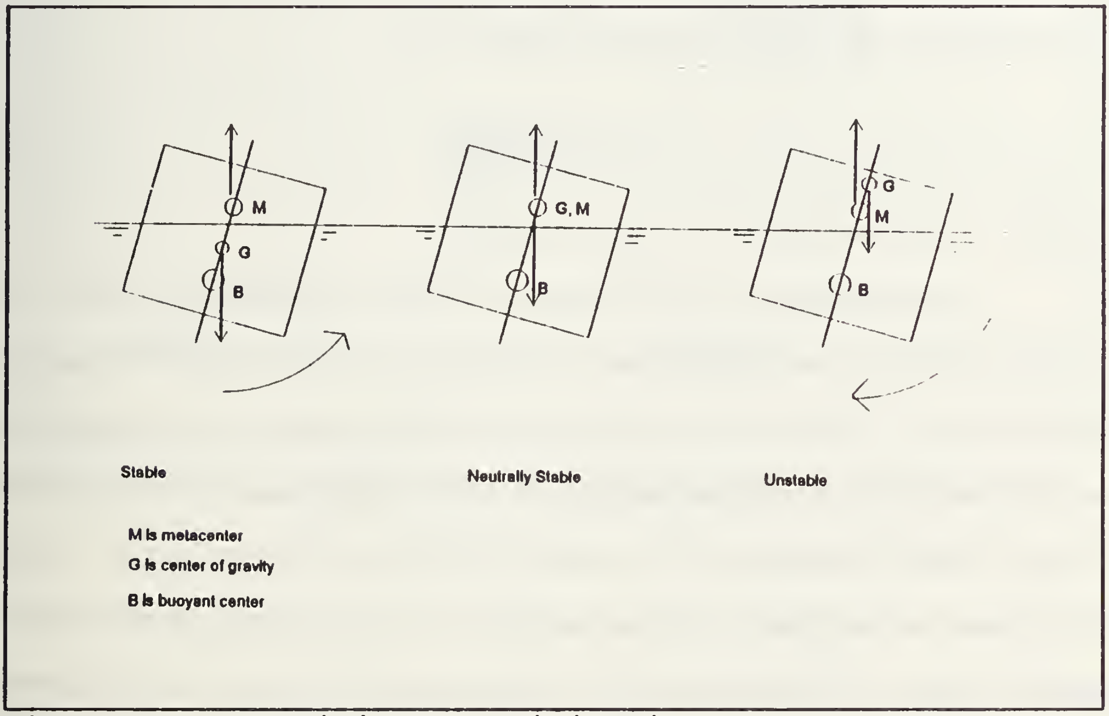

Figure 20: Stability Classification

For an initial analysis, the locations of the buoyant center and metacenter can be estimated by the simple expressions:

B = location of buoyant center = .42 to .45 x draft (below waterline)

BM = metacenter distance above B = I/V

where I is the waterplane moment of inertia and V is the volume of water displaced. The water plane is the cross sectional area of the vessel in the same plane as the water's surface, as shown in Figure 19. For standard ship shaped bodies,

$$I=\frac{Length x Beam^3}{18} \tag{8}$$

Alternately BM can be approximated by

$$BM=\frac{Beam^2}{12.6*D} \tag{9}$$

where D is the draft of the vessel.

Depending on the location of the wingship's wing, that large surface may contribute significantly to the wingship's stability. If the entire wing is in the water, the equivalent beam distance will be equal to the wingspan, which is much larger than the beam of a similar body without a wing. Figure 21 shows an example of this effect. The larger beam makes BM much larger, which moves the metacenter higher. If the center of gravity is in the same place, the winged vessel will be more stable than the one without the wing.

A wing also affects the rolling period of the vessel. This period can be approximated by

$$T=\frac{0.7*Beam}{\sqrt{(GM)}} \tag{10}$$

where GM is the distance between the center of gravity and the metacenter. Simply increasing the beam makes the rolling

period longer, but the metacenter also moves higher [Ref. 17: p. 53]. The net effect is to make a wingship act like a catamaran, with a sharp rolling tendency. The large beam will keep the wingship stable, but the roll magnitudes may be large.

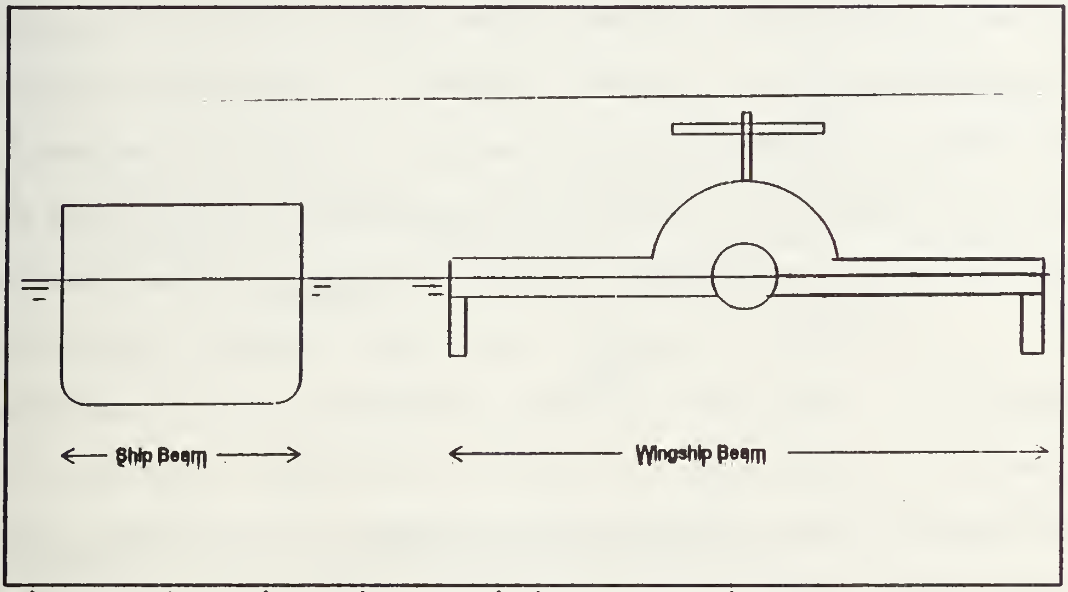

Figure 21: Wingship Stability Comparison

A major drawback to placing the wing at the waterline is the tremendous hydrodynamic drag penalty incurred during takeoff. There also would not be any trapped air volume available under the wing for the PAR cushion to form. An alternative would be to keep the wing above the static waterline and make the bottoms of the endplates into pontoons, which maintains the beam distance. This also increases takeoff drag, and adds greatly to the probability of damage during an endplate impact with the water during flight.

A third alternative is a pump and ballast system that allows the wing to remain above the water for takeoffs, and by flooding ballast tanks, the wingship can be lowered so that the wing can add to the stability. A potentially fatal situation occurs if the wingship is lowered and the pumping system to clear the ballast tanks fails. This would prevent the wingship from executing takeoff. Submarines routinely clear and flood their ballast tanks, so a similar system on a wingship should have similar reliability. The tanks and pumps add weight and complexity, which the designer must consider.

A wingship designer must also consider longitudinal stability. The form of the calculations for longitudinal stability is the same as that for transverse stability, but the length of the fuselage is used instead of the beam. While longitudinal stability is usually assured, the plowing of the forward fuselage must be considered. The engines are mounted in this area, and any direct water ingestion would be problematic. The designer must consider the design sea state when placing the engines and determining the static waterline.

3. Structural Considerations

Longitudinal wave motion affects the buoyant forces acting on the fuselage. If the seas are high enough, portions of the fuselage can leave the water. Since the vessel remains afloat, the total buoyant force remains the same, but the local force levels change as portions of the airframe enter

and leave the water, as shown in Figure 22. The structure of the fuselage must be designed to withstand a certain distribution of wave heights and spacings. Impact loads must also be considered, as the nose reenters the water.

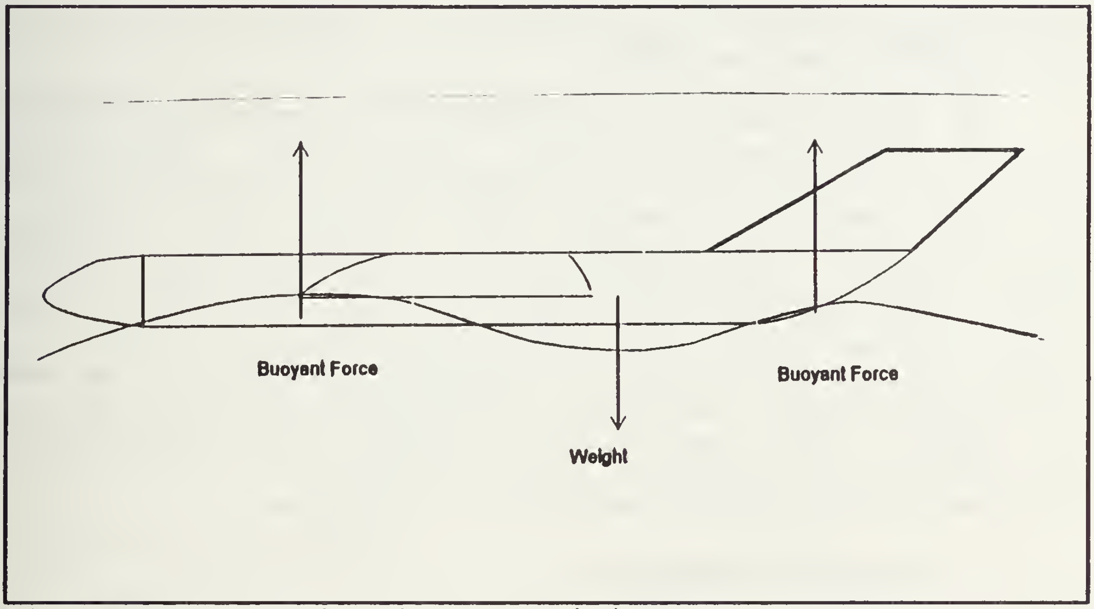

Figure 22: Longitudinal Stability

Transverse waves will create the same unsteady loading conditions on the wings. In heavy seas, the wings can enter and leave the water, creating hydrodynamic loads in both the upward and downward directions. The wing must be designed to handle these loads.

4. Conclusion

The wingship designer must consider sea conditions not only for takeoff and cruise performance reasons, but also for seakeeping reasons. From a tactical standpoint, the mission planner must consider the expected sea state in the mission

area before committing a wingship to the operation. This could prevent the use of wingships in stormy locations. A probability analysis of the specific area will aid in the decision to employ wingships.

C. TAKEOFFS AND LANDINGS

One of the tactical advantages of the wingship noted in Chapter II is the ability to rapidly move from point to point. The high dash and cruise speeds require the wingship to takeoff and land once per dash leg. Taking a 1000 ton vehicle from rest at sea to flight at 400 knots requires huge amounts of power. This section will discuss the unique problems involved in wingship takeoffs and landings.

1. Wingship Takeoffs

When a conventional aircraft takes off from a runway, its engines must accelerate it from rest to its takeoff velocity. During this takeoff roll, the engine thrust is opposed by aerodynamic drag and rolling resistance from the landing gear wheel surfaces. A wingship must gain its takeoff velocity against opposing aerodynamic, hydrodynamic, and wave generation forces.

Examination of the various forces acting upon a wingship taking off shows that the hydrodynamic (water) drag dominates the total resistive force. This force is

$$D_{water}=\frac{1}{2}\rho_w V^2 C_{f_w} d^2 \tag{11}$$

where ρ_w is the water density, V is the velocity, C_{fw} is the water drag coefficient, and d is the draft of the wingship at the instant in question. C_{fw} depends on the size and shape of the fuselage and other components (such as endplates) that are in the water. Sea water's density is approximately 1.99 slugs/cubic foot, while air's density at sea level is 0.0023769 slugs/cubic foot on a standard day. In other words, water is 837.225 times denser than air. For a heavy vehicle, the draft will be significant, and since the water's drag contribution is a function of the square of the draft, the total force can be huge.

While moving in or just above the water, a body generates waves that rise alongside it and travel outward. These waves require energy, which constitutes another form of drag. This is generally defined empirically, due to the complex interaction between the vessel, the water, and the air that creates these waves. Figure 23 shows one such empirical representation of the wave drag created under a surface effect vehicle. Reference 18 states that a wingship will have a similar wave drag response.

Besides creating additional drag sources, the water creates additional lifting forces. The wingship's static water displacement creates a buoyancy force, and the motion of the vessel creates a lift force, which is given by

$$L_{water} = \frac{1}{2} \rho_w V^2 C_{l_w} d^2 \qquad (12)$$

Note that the lift is also a function of the draft squared.

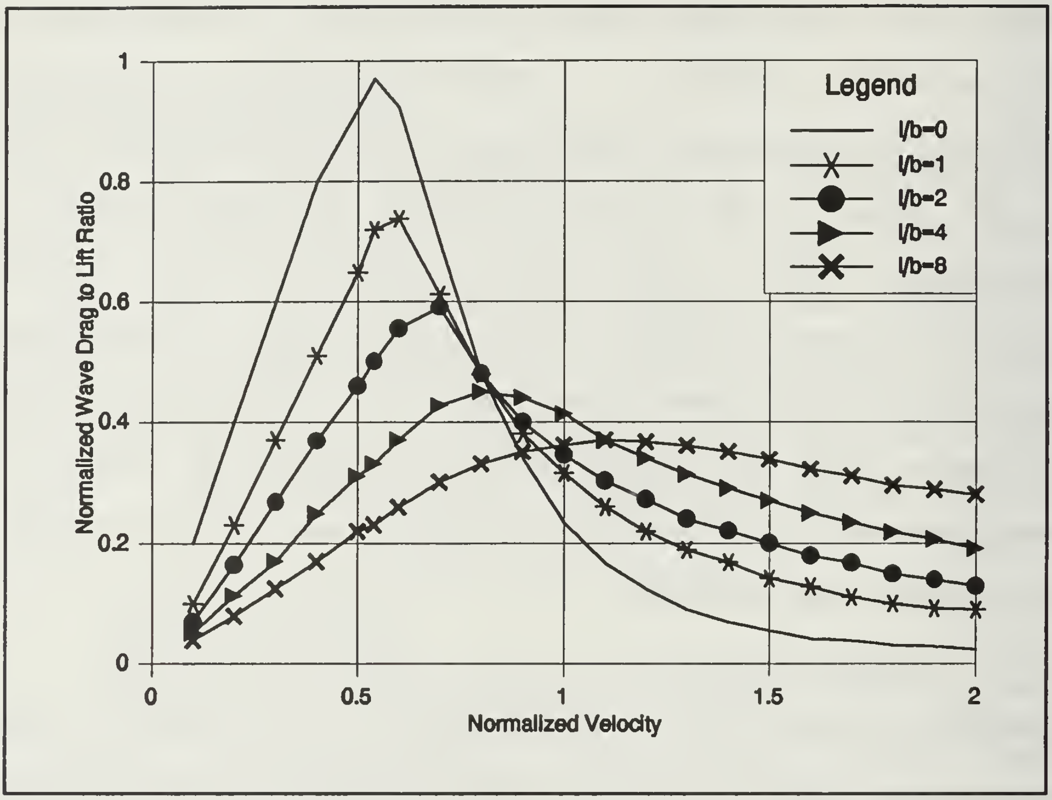

Figure 23: Water Wave Drag

The ram cavity under the wing creates a large amount of lift, as shown in equation 5. It can be quantified by

$$L_{Ram} = \frac{1}{2} \rho_{air} V_{jet}^2 C_p S \qquad (13)$$

Combining all the lift terms and equating them to the vehicle's takeoff weight produces an equilibrium equation

Weight = Ram lift + Aerodynamic lift + Water Lift + Buoyancy

or

$$W=\frac{1}{2}\rho_A V_{jet}^2 C_p S+\frac{1}{2}\rho_A V^2 C_L S+\frac{1}{2}\rho_w V^2 C_{f_w} d^2+C_B\rho_w d^2 \tag{14}$$

where the subscripts A and W denote air and water respectively. C_B in the buoyant force term is a proportionality constant dependant on the shape of the submerged portion of the vessel. If the hull has an irregular shape (as most high speed marine vessels do), it may be a function of draft and velocity. The equilibrium equation can be solved for the draft (d^2) terms for a given velocity.

Once the draft is known, it can be used to solve for the total drag:

Total Drag =(Endplate + Aerodynamic + Ram + Water + Wave) Drag

Endplate drag is the hydrodynamic drag of the wing endplates in contact with the water. This term is separate from the fuselage water drag because the endplates generally have different depths in the water than the fuselage. Ram drag is created by the loss in propulsive force due to the under wing ram effect, and is given by

$$D_{ram}=\frac{1}{2}\rho_A V_u^2 C_{D_R} S \tag{15}$$

where C_{dR} is a function of the wing geometry and V_U is the air velocity under the wing. Equation 6 shows the thrust coefficient for a ram wing, which is defined as the ratio of

recovered thrust to the thrust produced by the engines. This is another expression for the ram drag.

The total drag for each velocity can now be determined. For a simplified version of Figure 1's configuration, Figure 24 shows the contribution of the various components. The geometry of the fuselage is simplified here as a simple square body to simplify the functional relationship between hydrodynamic forces and fuselage depth in the water.

This curve shows an obvious maximum drag at approximately 71 knots. This is known as the hump. At this velocity, the largest thrust is required from the engines. For cruise in ground effect, the thrust required is

$$T=D=\frac{1}{2}\rho_A V^2 S\left(C_{D_o}+\frac{C_L^{\,2}}{\pi e AR_{eff}}\right)+wave\ drag \qquad \textbf{(16)}$$

which, for the same example configuration, is shown in Figure 25.

Using the data discussed in Section IV(A) above, the takeoff runs for this example wingship in several sea states are shown in Table V, and plotted in Figure 16.

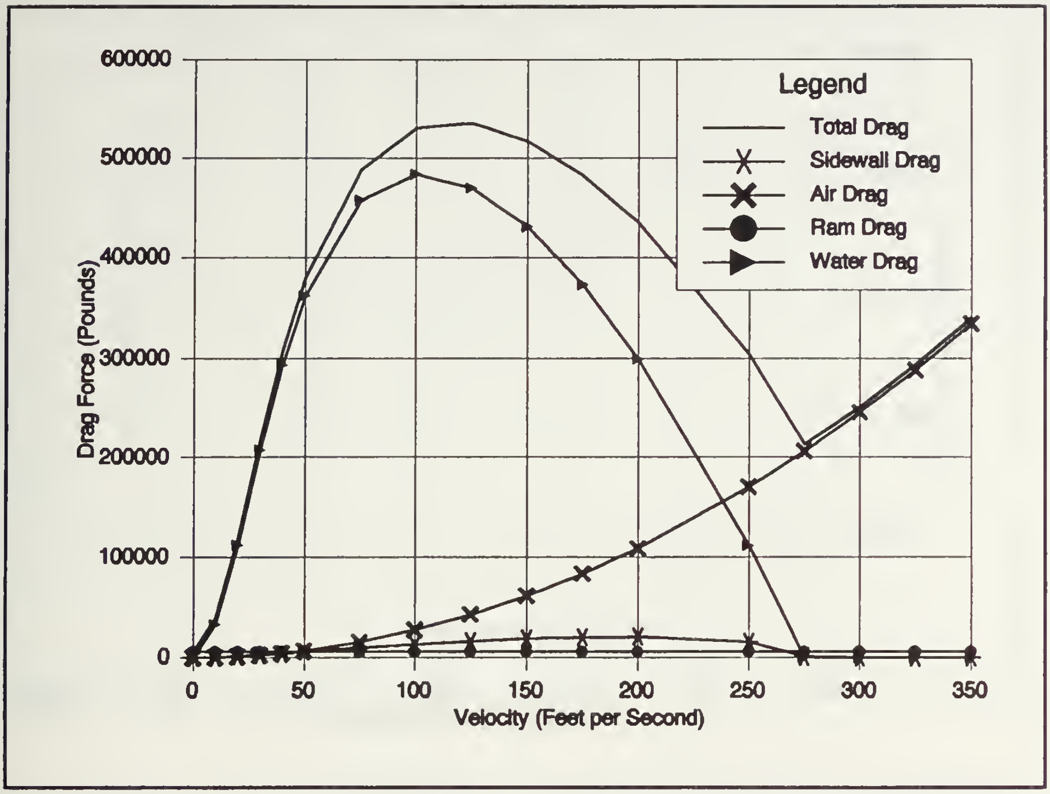

Figure 24: Takeoff Drag

TABLE V: WINGSHIP TAKEOFF RUNS

Significant Wave Height	Takeoff Distance (Feet)
1	17276
4	21583
12	32245

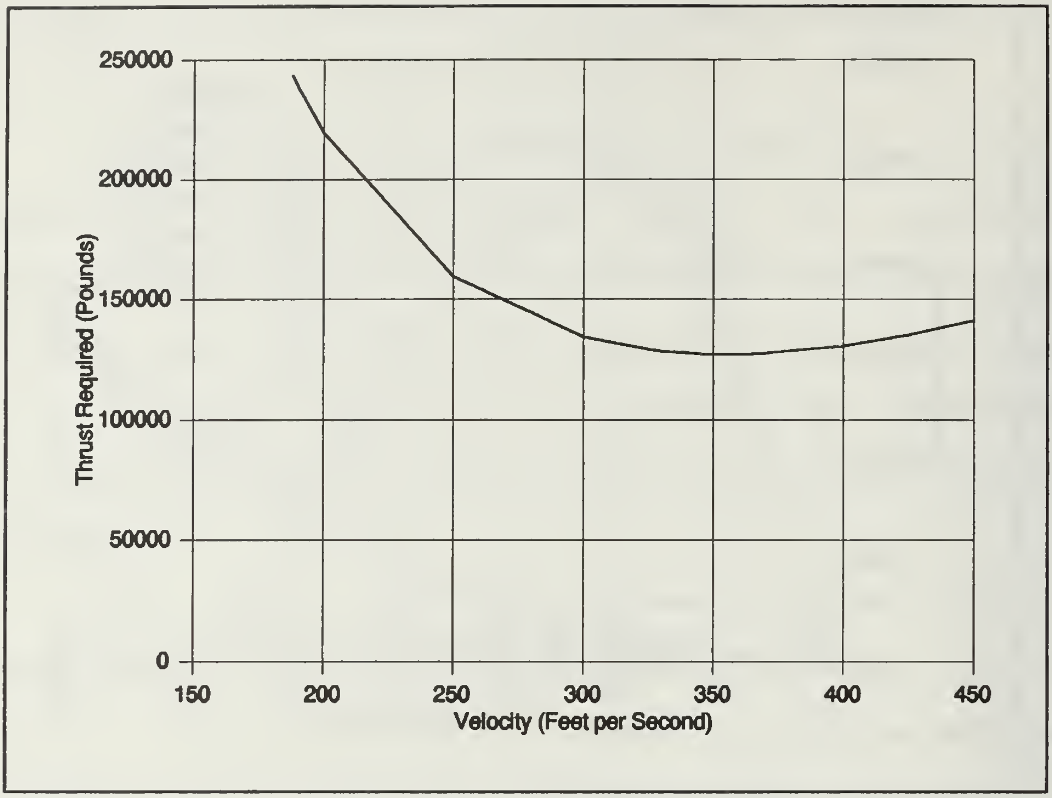

Figure 25: Takeoff Thrust Required

Figure 26 shows the fuel required for takeoff in these conditions. Figure 27 shows the effect of multiple takeoffs on overall mission range.

The mission planner must consider the effect of takeoffs on mission range when scheduling wingship operations. Missions requiring numerous takeoffs and landings will have a smaller overall unrefueled range.

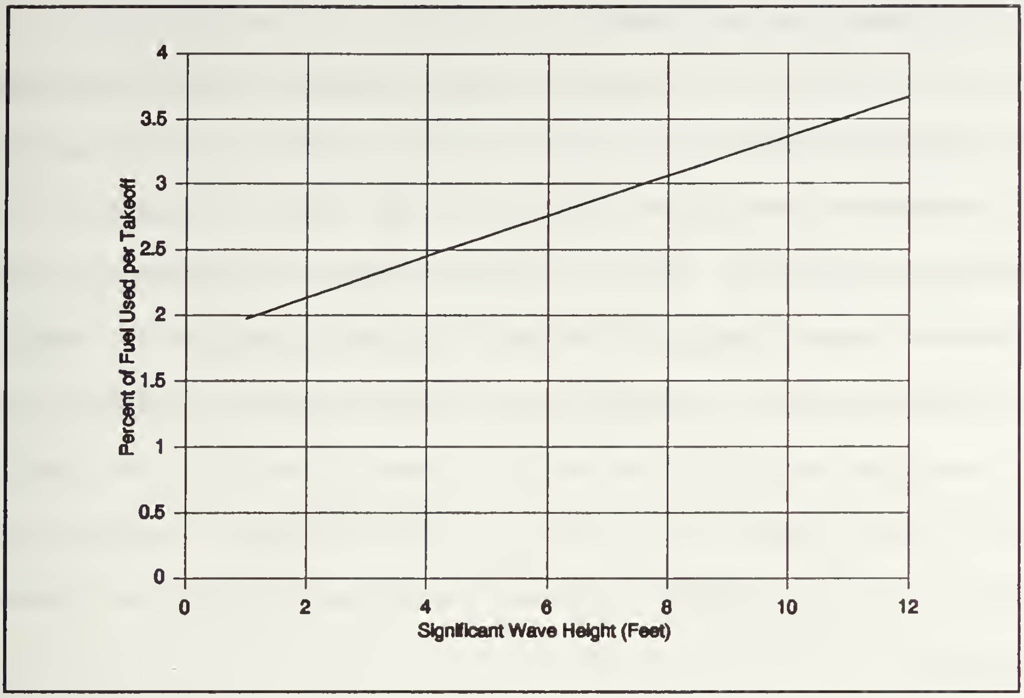

Figure 26: Takeoff Fuel Required

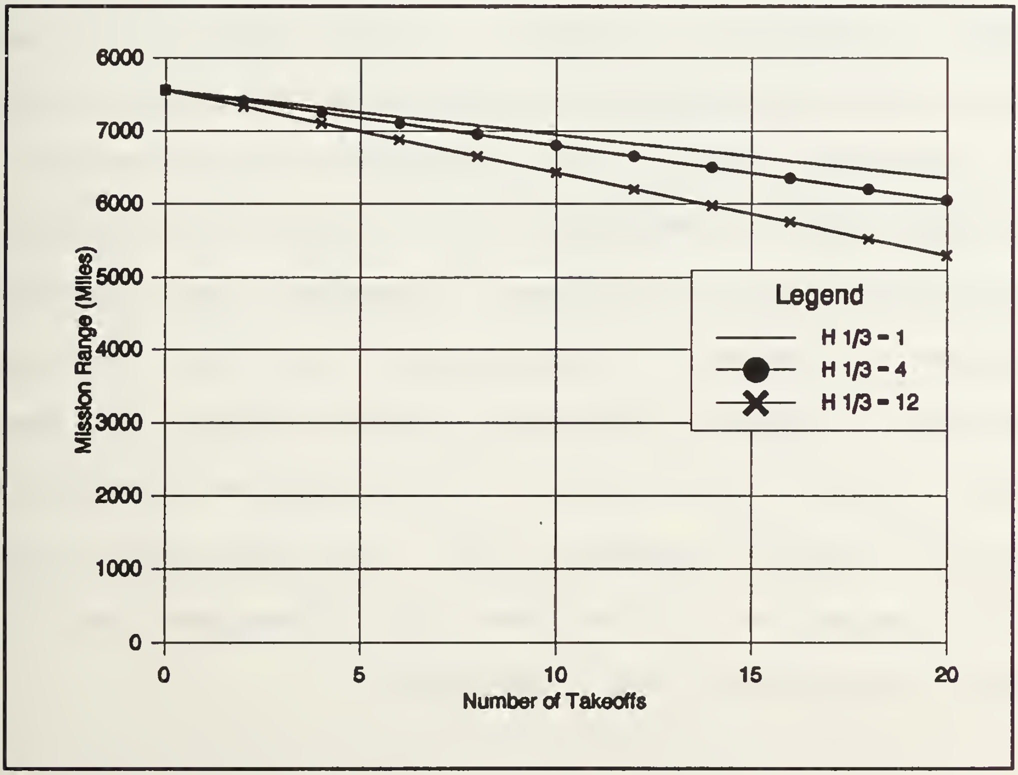

Figure 27: Mission Range Versus Number of Takeoffs

2. Wingship Landings

In order to enter the water at a reasonable velocity, the wingship must reestablish the PAR cushion before landing. This requires additional thrust, but not as much as that needed for takeoff. Until the fuselage and endplates enter the water, the only additional thrust required above the cruise requirement is that needed for the PAR cushion. Once the fuselage enters the water, power can be cut and the vehicle will coast to a stop. The wingship designer must account for the impact forces when designing the fuselage structure.

3. Engine Out Performance

A wingship requires symmetric ram lift in order to conduct a takeoff or landing. In the event of an engine failure, one side of the PAR cushion will experience more lift than the other, causing an undesirable rolling moment. If sufficient power is available for an engine out takeoff, the aircraft must have an automatic asymmetry load alleviation mechanism to prevent a catastrophic roll into the water. Reference 19 suggests either an automatic engine shutdown on the side opposite the failure, or preferably an automatic flap retraction on that opposite side. The flap would retract enough to equalize the PAR load, and allows the use of all remaining engines for the takeoff run.

A tactically useful wingship would require the capability for a takeoff with an engine out. If the aircraft was grounded by a single engine failure, a minor weapon hit or water ingestion could terminate the mission. With the high risk of foreign object ingestion and the long potential duration of the design missions, sufficient thrust margins to allow an engine out takeoff are required.

V. COST ANALYSIS

A. INTRODUCTION

The added tactical capability provided by the combatant wingship will require a substantial financial investment. Development of a revolutionary vehicle will probably take several years in today's acquisition environment, and cost billions of dollars. Each production vehicle will itself cost many dollars, and only a large quantity buy will drive this cost down. Similarly, the costs to operate a wingship or fleet of wingships will be significant. This chapter will discuss the estimated costs to develop, procure, and operate a combatant wingship. These costs will be compared to the costs of acquiring and operating similar combatant warships.

B. DEVELOPMENT AND PRODUCTION COSTS

The proposed wingship is much larger than any current aircraft. The cost estimating relations (CERs) cited by the literature use existing aircraft data to predict the costs of proposed aircraft by interpolation or extrapolation only slightly beyond the range of observed data. The wingship requires extrapolation far beyond the scope of the statistical data, which leads to a large degree of uncertainty in the results. Since there are no comparable methods upon which to

base an estimate of wingship costs, three published CER sets will be used.

1. Cost Models

The three cost estimating models used were the Nicolai method [Ref. 16: pp. 24-8 through 24-20], the Rand recommended method [Ref. 20: p.4], and the Rand DAPCA III method [Ref. 20: p. 115]. This section will define these three methods.

a. *Nicolai Method*

This method differentiates between the Development, Test, and Engineering (DT & E) phase and the Production phase of the aircraft acquisition cycle. It is an older method, based on a 1971 Rand Corporation study.

The Nicolai method uses the following abbreviations:

1. A is the Aeronautical Manufacturers Planning Report weight (AMPW). This includes the empty weight of the aircraft, without wheels, tires, engines, cooling fluid, fuel cells, instruments, electrical power supplies and batteries, avionics, trapped fluids, air conditioners, and auxiliary power units. For the 1000 ton design wingship, the baseline value for A is estimated to be 980,000 pounds.
2. S is the maximum speed, in knots. The baseline maximum speed for this wingship is 450 knots.
3. Q_d is the quantity produced during the DT & E phase. The baseline for this analysis is one aircraft.

4. Q_p is the quantity produced during the production phase. For this study, the baseline production run is nine aircraft, making the cumulative total program quantity ten.

5. R is the production rate during the production phase. This is assumed to be one aircraft per month.

6. R_{DTE} is the production rate during the DT & E phase. Since only one aircraft will be built in this phase (the baseline case), the rate is one.

7. T is the maximum thrust per engine. It is assumed to be 50,000 pounds for the baseline case.

8. N_{eng} is the number of engines. This proposed wingship will have eight engines.

The Nicolai method requires hourly rates for engineering, tooling, quality control, and manufacturing. From Reference 21, these rates in 1986 were:

1. Engineering: $59.10
2. Tooling: $60.70
3. Quality Control: $55.40
4. Manufacturing: $50.10

These rates are multiplied by the their respective CER hourly quantities to obtain the cost for that element.

The non-hourly CERs are based on 1970 dollars. To convert them from 1970 dollars to 1995 dollars, these costs were multiplied by an inflation factor of 1.75 [1970-1977, Reference 18] and then by 2.6632 [1977-1995, Reference 22], for a combined multiplier of 4.6606. This puts all costs in

consistent 1995 dollars, which are standard for this report's production cost comparisons.

The Nicolai cost estimating relations for the DT & E phase are as follows:

1. Airframe engineering hours = $0.0396A^{.791}S^{1.526}Q_d^{.183}$
2. Development support = $0.008325A^{.873}S^{1.890}Q_d^{.346}$
3. Flight test operations = $0.00124A^{1.16}S^{1.371}Q_d^{1.281}$
4. Tooling Hours = $4.0127A^{.764}S^{.899}Q_d^{.178}R_{DTE}^{.066}$
5. Manufacturing labor hours = $28.984A^{.740}S^{.543}Q_d^{.524}$
6. Quality control hours = 0.13(Manufacturing labor hours)
7. Manufacturing material = $25.672A^{.689}S^{.624}Q_d^{.792}$
8. Engines = $130T^{.8356}N_{eng}Q_d$

The CERs for the production phase are as follows:

1. Airframe engineering hours = $0.0396A^{.791}S^{1.526}(Q_d+Q_p)^{.183}$- DT&E airframe engineering hours
2. Tooling Hours = $4.0127A^{.764}S^{.899}(Q_d+Q_p)^{.178}R^{.066}$- DT&E tooling hours
3. Manufacturing labor hours = $28.984A^{.740}S^{.543}(Q_d+Q_p)^{.524}$- DT&E manufacturing labor hours
4. Quality control hours = 0.13(Manufacturing labor hours)
5. Manufacturing material = $25.672A^{.689}S^{.624}(Q_d+Q_p)^{.792}$- DT&E manufacturing material
6. Engines = $130T^{.8356}N_{eng}Q_p$

The hourly CERs reflect the learning curve effect carried over from the DT & E phase. The quantity produced includes the DT

& E aircraft inside the formula, but the individual effect of the DT & E quantity is subtracted from the combined total.

The Nicolai CERs are validated against the Cessna Citation example as shown in Reference 16. These calculations are shown in Appendix A. Appendix B shows the contributions of the different components of the cost models to the overall program costs.

b. Rand Recommended Method

The two Rand methods do not distinguish between the DT & E and production phases. Their recommended set of CERs is based on a 1987 study [Ref. 20].

The Rand recommended method uses the following abbreviations:

1. EW is the aircraft empty weight in pounds. The baseline for the wingship is 1400000 pounds.
2. S is the maximum speed, in knots. The baseline speed is 450 knots.
3. N_{test} is the number of flight test aircraft. For this case, the baseline is one.
4. N is the total number of aircraft produced for the entire program. The baseline for this analysis is 10.

The labor rates are the same as for the Nicolai method. The basic set of CERs is based on 1977 dollars, so an inflation multiple of 2.6632 was used to scale the costs to 1995 values.

The Rand recommended CERs are as follows:

1. Engineering $hours_{100} = 10.3EW^{.777}S^{.894}$

2. Tooling $hours_{100} = 20.1EW^{.777}S^{.696}$

3. Manufacturing $hours_{100} = 141EW^{.820}S^{.696}$

4. Manufacturing $materials_{100} = 241EW^{.921}S^{.621}$

5. Development support $= 25.1EW^{.630}S^{1.30}$

6. Flight test $= 687EW^{.325}S^{.822}N_{test}^{1.21}$

7. Quality control $hours_{100}$ = 0.133(Manufacturing $hours_{100}$)

Items 1, 2, 3, 4, and 7 are normalized to a production run of 100 total aircraft. To convert these to an arbitrary number of aircraft (N), the following conversions are used:

1a. Engineering hours = (Engineering $hours_{100}$)$(.01N)^{.163}$

2a. Tooling hours = (Tooling $hours_{100}$)$(.01N)^{.263}$

3a. Manufacturing hours = (Manufacturing $hours_{100}$)$(.01N)^{.641}$

4a. Manufacturing materials = (Manufacturing $materials_{100}$)x $(.01N)^{.799}$

7a. Quality control = (Quality $control_{100}$)$(.01N)^{.641}$

c. Rand DAPCA III Method

This is an older method that predates the Rand recommended method. It was used as a comparison in Reference 19 to validate the recommended CERs. The baseline values and abbreviations are the same as those listed for the Rand recommended CERs. An additional variable is cargodv, which is an algebraic flag denoting whether or not the aircraft is a

cargo transport. The value is 2 if the aircraft is a cargo aircraft, and 1 if it is not. The baseline is 1.

The DAPCA III CERs are as follows:

1. Engineering $hours_{100} = 23.4EW^{.656}S^{.960}$
2. Tooling $hours_{100} = 472EW^{.638}S^{.499}$
3. Manufacturing $hours_{100} = 353EW^{.793}S^{.423}$
4. Manufacturing $materials_{100} = 76.3EW^{.880}S^{.867}$
5. Development support $= 0.626EW^{.688}S^{1.21}+.0354EW^{.724}S^{1.92}$
6. Flight test $= 192EW^{.710}S^{.586}N_{test}{}^{.716}Cargodv^{-1.56}$
7. Quality control $hours_{100} = 0.12$(Manufacturing $hours_{100}$)

Again, items 1, 2, 3, 4, and 7 are normalized to a quantity of 100 aircraft. To scale to an arbitrary amount N, the same exponential corrections as in section 1(b) above are used.

2. Wingship Costs

Figure 28 shows the total program cost, in 1986 dollars, for baseline wingships produced in various quantities. Figure 29 shows the average cost per wingship for the same production quantities. All three methods show the expected decrease in unit cost with increased purchase quantities. For a total quantity of ten aircraft, the estimated cost ranges between $1.398 billion and $3.304 billion. Total program cost is ten times these amounts.

These cost figures do not include the cost for avionics, which can comprise up to half the total cost of the aircraft. Contractor profit is not included either. These

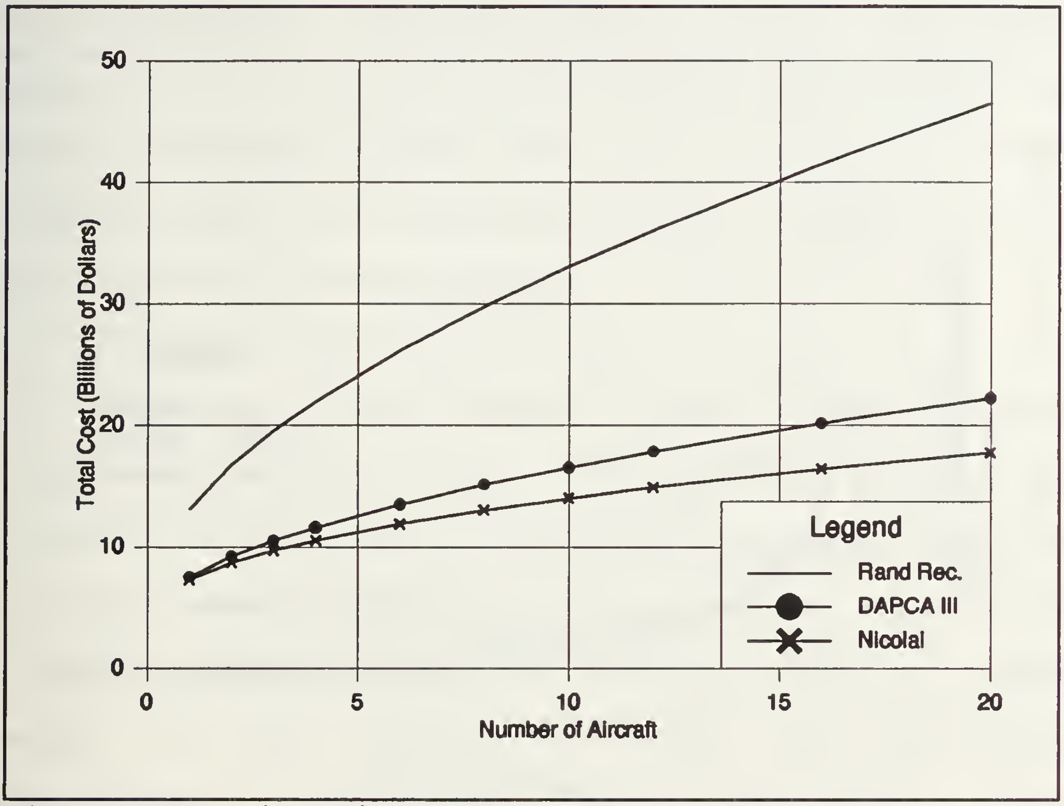

Figure 28: Wingship Program Cost

two factors can double the estimated costs, so each of the ten wingships could cost between \$2.796 billion and \$6.608 billion. This doubling is not included in the cost sensitivity analysis section, but is included for comparison with surface vessel cost. The program costs for surface vessels includes their electronic systems and contractor profit, so a meaningful comparison between these costs and a wingship's costs must also include them.

The Rand recommended method provides costs approximately two times higher than those of the other two methods. These CERs are newer than the other sets, and include consideration of advanced materials and manufacturing

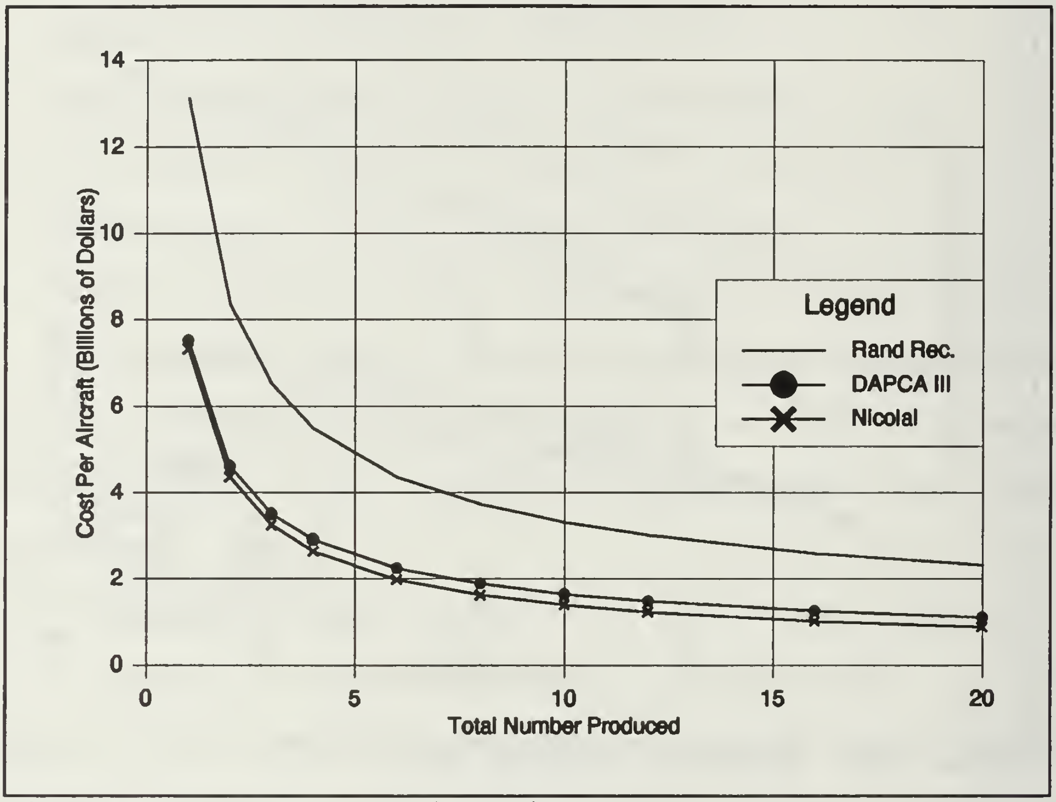

Figure 29: Cost Per Wingship

techniques. Advanced methods can increase the cost of an aircraft, so the higher values may not be unreasonable. Since the wingship requires an extrapolation beyond the statistical limits of the samples of all three methods, there is no basis for rejecting any of them. Therefore, the Rand recommended result will be considered the upper bound cost and the Nicolai will be considered the lower bound.

Figure 29 shows that a purchase of only one wingship (a technology demonstrator) would cost up to $13.121 billion. This would comprise a large portion of even the largest defense budget. For double the investment, five more vehicles could be purchased. The developmental and test costs for the wingship would be spread over several years, which would lessen the budgetary burden. But, for a given size, as Figure 29 clearly shows, the only way to drive the cost down over time is to buy a larger quantity.

3. Wingship Cost Sensitivities

This section will discuss the sensitivity of wingship cost to several design factors. The CERs that generate these cost estimates are empirical and cannot be used to determine causal relationships between a design parameter and its effect on vehicle cost. Unmodeled factors, such as advanced materials or wing loading, for example, may also directly affect wingship program cost. Since these factors are not included in the CERs, they are not covered here. This section will cover the cost trends expected by varying aircraft weight and number of flight test aircraft.

Figure 30 shows the effect of aircraft weight (measured as AMPW) on the cost for a program of ten wingships, using the Nicolai model. Figure 31 shows the same data, using the aircraft empty weight and the two Rand cost estimating models. These figures are plotted separately since the AMPW

weight and the aircraft empty weight are two different quantities, and the relationship between them can be manipulated by the designer.

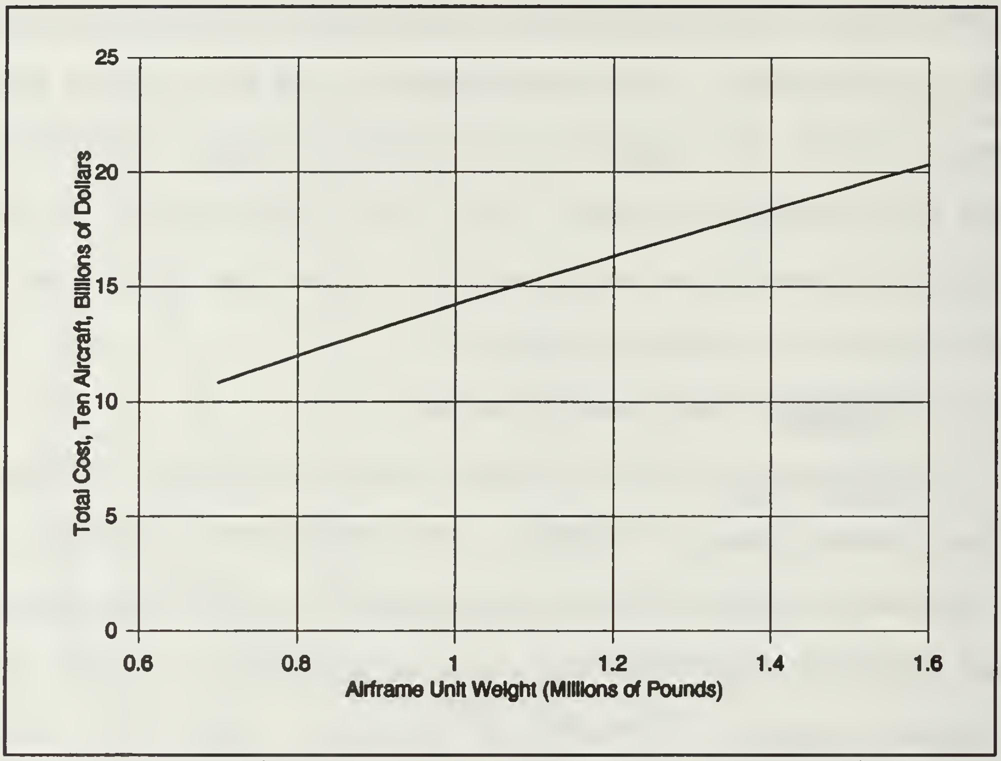

Figure 30: Wingship Cost Versus Airframe Unit Weight

Figure 30 shows a slope of $1058.5 per pound of AMPW weight per aircraft. A ten percent reduction in wingship AMPW (980,000 pounds to 882000 pounds) would reduce the program cost by $1.037 billion, or $103.732 million per aircraft.

Figure 31 shows a slope of $19623.59 per pound of empty weight for the Rand recommended method, and $8965.22 per pound for the DAPCA III method. For a ten percent reduction in empty weight, the program cost is reduced by $2.748 billion and $1.255 billion respectively.

Both figures combined show a stronger absolute weight influence for the Rand recommended calculations. Alternately, the ten percent weight reduction reduced the program cost by 7.41%, calculated using the Nicolai method. For the Rand recommended method, the same weight reduction decreased the program cost by 8.32%, and the DAPCA III method shows a reduction in cost of 7.61%. With program costs in the billions of dollars, all three methods agree that weight reductions can significantly lower program costs.

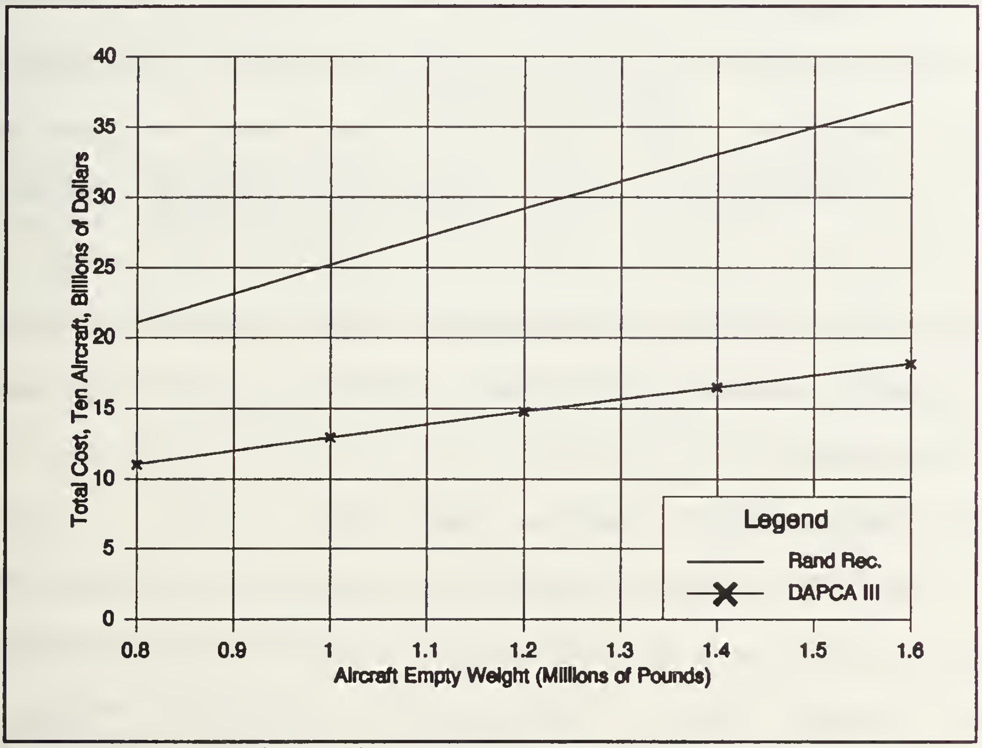

Figure 31: Wingship Cost Versus Empty Weight

Figure 32 shows the effect of the number of flight test aircraft on program cost. The actual program cost values (in billions of dollars) are shown in Table VII.

TABLE VII: PROGRAM COST VERSUS NUMBER OF FLIGHT TEST AIRCRAFT

Method	One Test Article	Two Test Articles
Nicolai	13.982	14.487
Rand Recommended	33.043	33.081
DAPCA III	16.489	16.761

All values are calculated for a total production run of ten vehicles, including the flight test aircraft. As percentage cost increases, the change to two test aircraft increases the Nicolai baseline total by 3.61%, the Rand recommended by 0.11%, and the DAPCA III by 1.65%. In all cases, the economy of scale present in full production reduces program cost over time, but during development each aircraft must be individually produced "by hand". This will tend to increase the total cost.

4. Comparison to Surface Ship Cost

In 1995 dollars, the total program cost for the DDG-51 Arleigh Burke class destroyer is $950.2 million per ship (25 total, through 1993). The cost for the CG-47 Ticonderoga class cruiser was $1.033 billion per ship, with a quantity of 27 through 1993. The baseline wingship, as shown in Section 5(b)3 above, costs between $2.796 billion and $6.609 billion, including avionics and weapons. These figures show that the

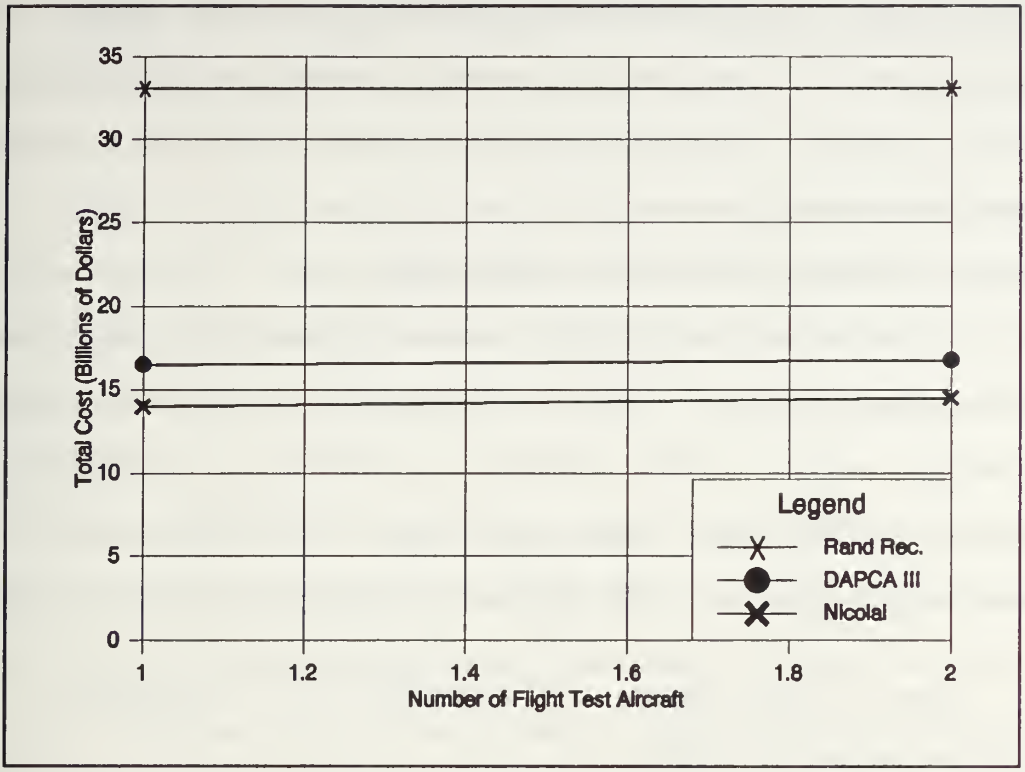

Figure 32: Total Wingship Program Cost Versus Number of Flight Test Aircraft

wingship is several times more expensive than today's surface combatants. The next section will compare the estimated annual operating costs for wingships and these same surface vessels. Chapter VI will cover several measures of effectiveness, accounting for platform cost, operating cost, and tactical usefulness.

C. OPERATING COSTS

This section will discuss the costs to operate wingships and surface ships. Empirical models are used for each type of ship due to the variable nature of actual ship operations and their sensitivity to real world operational missions and

restrictions. By comparing generic empirical costs, fleet averages can be compared. Appendix B shows the contributions of the various components to the overall ship and wingship annual operating costs.

1. Wingship Operating Cost Model

The Naval Fixed Wing Aircraft Operating and Support Cost Estimating Model [Ref. 23] was used to estimate wingship operating costs. This method is based on constant 1990 dollars, which are then converted to 1995 dollars for comparison purposes. The following abbreviations are used:

1. Na is the number of aircraft in a squadron. The baseline value is eight.

2. Mgtw is the maximum gross takeoff weight, in pounds. The baseline wingship has a maximum weight of 1000 tons, or 2000000 pounds.

3. Enlmnt is the number of enlisted maintenance personnel. This value is calculated as a preliminary calculation in the CER set.

4. Offmnt is the number of officers in the squadron maintenance department. The baseline value is five.

5. Enloup is the number of other enlisted personnel in the squadron. This includes administrative personnel, medics, cooks, etc. The value is calculated as part of the aircraft operating CER set.

6. Offoup is the number of other officers in the squadron. This primarily includes the squadron staff. The baseline value is 10.

7. Rwper is the average percentage of aircraft undergoing airframe rework. The baseline is assumed to be ten percent. This value will not take effect until the wingships have been in service for a period of time, but is included for completeness.

8. S is the average cruising speed, measured in feet per second. A 400 knot cruise equals 675.12 feet per second.

9. AB is a methodology flag denoting whether or not the aircraft engines have afterburners. The value is one if it does, and zero if it does not. The wingship does not have afterburning engines, so the value here is zero.

10. Thrust is the average thrust per engine. The baseline is 50000 pounds.

11. Mtbr is the mean time between engine repairs. The baseline is 100 hours.

12. Numeng is the number of engines on the wingship. The baseline is 8.

13. TF is a turbofan engine methodology flag. It has a value of one if the aircraft has turbofan engines, and zero if it does not. The wingship does have turbofan engines, so the value is one.

14. Ewasw is a methodology flag for electronic warfare or antisubmarine aircraft. The baseline value is zero, since the wingship is not executing these missions.

15. Time is the average mission duration, in hours. Since the wingship will conduct long duration missions that include long periods sitting on the surface, a value of 13 hours was chosen as a baseline. This corresponds to a maximum range cruise, followed by a period of sea sitting.

The wingship operating cost estimating relations are as follows:

1. Unit personnel cost =[(number of officers/aircraft)x (officer pay)+(number of enlisted/aircraft)(enlisted pay)]x Na The office and enlisted pay rates are the "composite standard rates", or the weighted averages of the costs to the Navy of compensating the officers and enlisted personnel who operate, maintain, and support the aircraft. Reference 23 states that the officer rate for 1990 was $66051, and the enlisted rate was $28243.

2. $\text{Enlmnt} = 48.71\text{Na}^{-.5091}$

3. Maintenance personnel cost = (offmnt)(officer pay)+ (enlmnt)(enlisted pay)

4. $\text{Enloup} = 40.34\text{Na}^{-.904}$

5. Other unit personnel cost = (offoup)(officer pay)x (enloup)(enlpay)

6. Fuel per flight hour = $.00000016\text{Mgtw}^{.4926}\text{S}^{1.646}(1.412)^{\text{AB}}$ (in gallons)

7. Fuel cost = (fuel/flight hr)(flight hrs/year)(cost per gallon of fuel)

8. Support supplies cost = $719.96Na^{-.6522}$

9. Training ordnance = 19.536+.0427(mission radius)

10. Airframe rework cost = $.0166(\text{empty wt})^{1.0281}(\text{rwper})$

11. Engine rework cost = $.001876(\text{thrust})^{1.2305}(.3329)^{AB}$x (flight hours per year)(numeng)/mtbr

12. Component rework cost = $.01116(\text{empty wt})^{.3455}(1.5658)^{TF}$x (flight hours per year)

13. Other depot support costs = $.001117(\text{mgtw})^{.8638}(1.4388)^{ewasw}$

14. Ground support equipment cost = $.1965(\text{time})^{.4517}$

These costs do not include costs for emergency repairs, contractor technical services, or modification costs. Cost inputs (the officer and enlisted pay rates) are made in thousands of 1990 dollars, and the cost outputs are in thousands of 1990 dollars. Once the final amount is determined, it is converted to 1995 dollars using an inflation multiplier of 1.1268 [Ref. 24].

2. Ship Operating Cost Model

An Office of Naval Research report [Ref. 25] was used to estimate the annual operating costs of Ticonderoga class cruisers and Arleigh Burke class destroyers. This report bases its costs on 1976 dollars, so an inflation multiplier of 2.9046 [Ref. 24] was used to convert these to 1995 dollars. Reference 25 provided the ship data listed below. The

following abbreviations are used in the ship operating cost estimating relations:

1. Off is the number of officers per ship. There are 23 officers per Burke destroyer and 24 officers per Ticonderoga class cruiser.

2. Enl is the number of enlisted sailors per ship. There are 280 per destroyer and 334 per cruiser.

3. Offpay, enlpay are the same composite standard pay rates used for the wingship operating cost estimates.

4. Crew is the total number of crewmen on the ship. It is the sum of the officers and enlisted sailors.

5. SAP is the total shaft horsepower per ship. A destroyer has 105000 shaft horsepower, and a cruiser has 86000.

6. Nucdummy is a nuclear power methodology flag. It has a value of one if the ship is nuclear powered, and zero if it is not. Both classes of ships here are not nuclear, so nucdummy is zero for both.

7. Disp is the total hull displacement, in tons. A destroyer displaces 9033 tons, and a cruiser displaces 9466 tons.

8. Hours is the total steaming hours per year, including underway and not underway hours. The baseline was 1000 hours for both ship classes.

The ship operating cost estimating relations are as follows:

1. Personnel cost = (off)(offpay)+(enl)(enlpay)

2. Temporary additional duty (TAD) = -1845.64 + 36.205 x (crew)

3. Fuel cost per steaming hour = 212.082 + .001462(disp) + .00105(SAP) - 381.7(Nucdummy)

4. Repair parts cost per steaming hour = 28.083 + .00263 x (disp)

5. Supplies cost = 44797.515 +248.26(crew) + 478.83(Nucdummy)

6. Purchased services cost = 48480 + 8.845(disp)

7. Intermediate maintenance cost per steaming hour is determined by the type of ship, as per Table VIII.

TABLE VIII: INTERMEDIATE MAINTENANCE COST PER STEAMING HOUR

Ship Type	Cost per Steaming Hour ($)
DD	12.30
FFG	13.80
FFG	21.40
DD	20.20
CG	10.10
CV	1.00
CGN	1.90
CVAN	3.20

8. Unscheduled repairs cost per steaming hour = 28.838 + .01471(disp)

Items 3, 4, 7, and 8 are multiplied by the number of hours per year the ship spends steaming. As defined above, this includes powered hours underway, and in port.

3. Wingship Operating Cost Analysis

Figures 33 and 34 show the annual wingship operating costs for different squadron sizes. The line does not pass through the origin, showing a significant overhead cost for even one aircraft. Figure 34 shows this overhead cost effect more clearly. The infrastructure required to operate even one aircraft is quite large, and includes a unit staff, intermediate maintenance personnel, and a repair parts supply system.

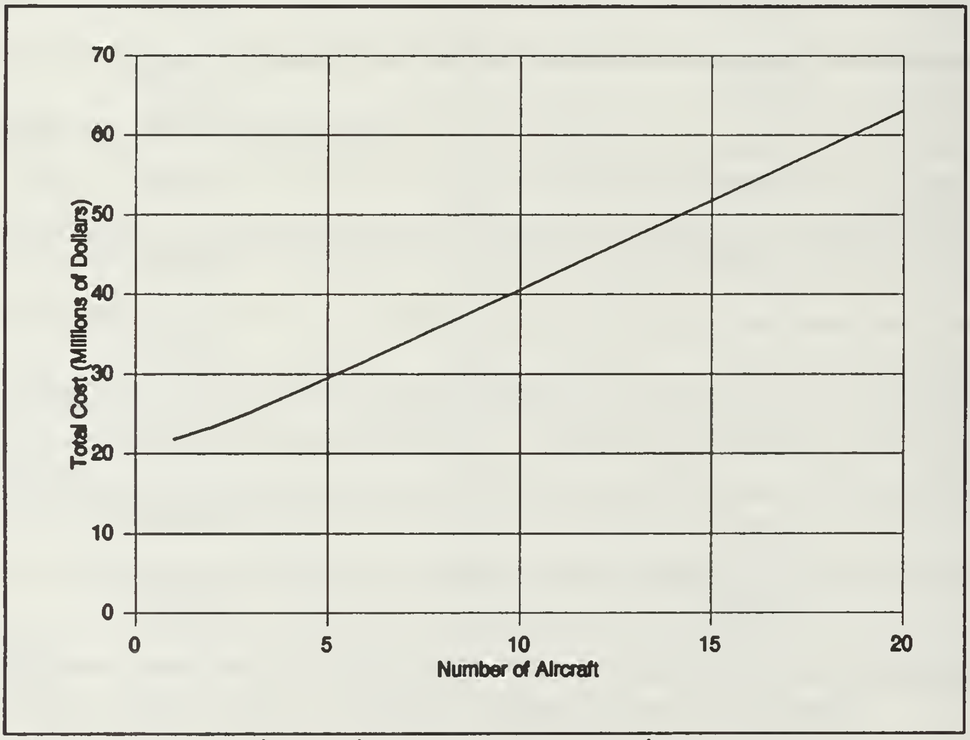

Figure 33: Wingship Total Operating Cost

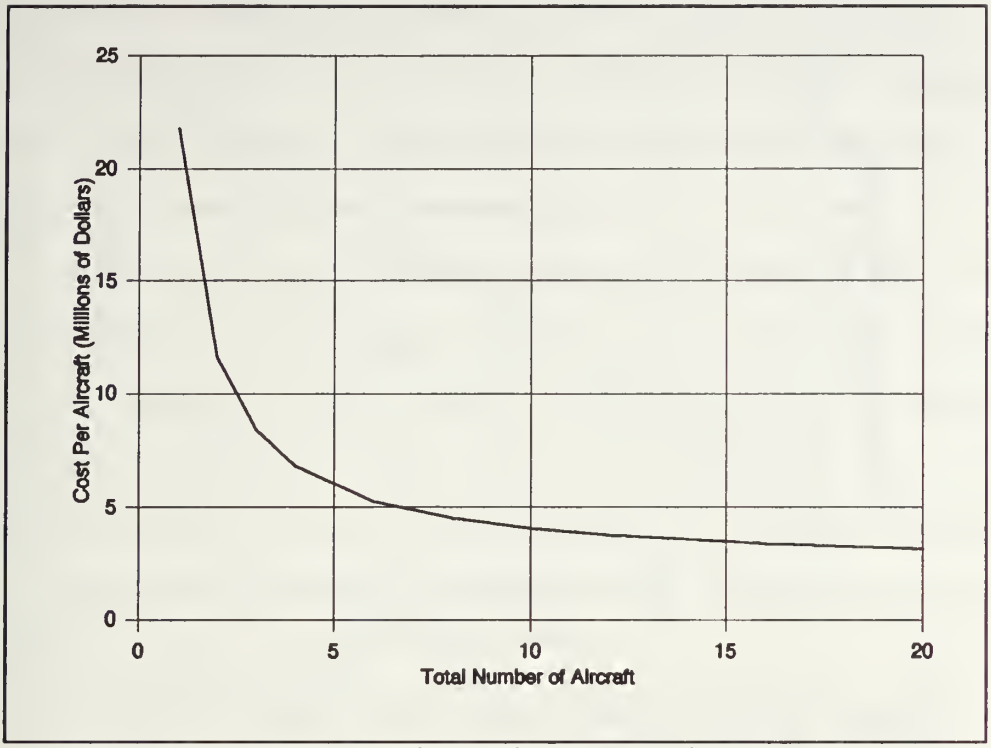

Figure 34: Average Wingship Operating Cost Versus Number of Aircraft

Figures 35 and 36 show the strong effect of annual flying hours on wingship operating cost. Again, the relationship is linear. Figure 36 shows a slope of $115497 per flying hour. An increase in ten percent of annual flight hours per aircraft (from 100 to 110) would change the average annual cost by $1.155 million, or 25.6%. This strong dependence of cost on flight hours is expected, since "operating" means "flying" for an aircraft, and time spent in operation requires fuel, parts, and maintenance man hours.

These sets of figures show an average cost of $4.506 million per wingship operating 100 hours per year, and $8.833

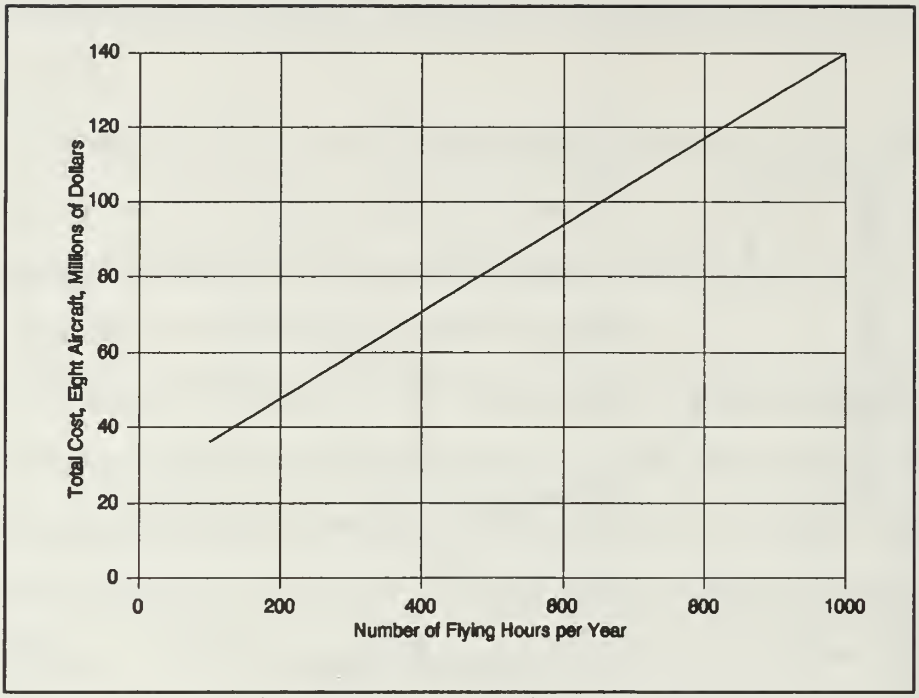

Figure 35: Wingship Operating Cost Versus Annual Flight Hours

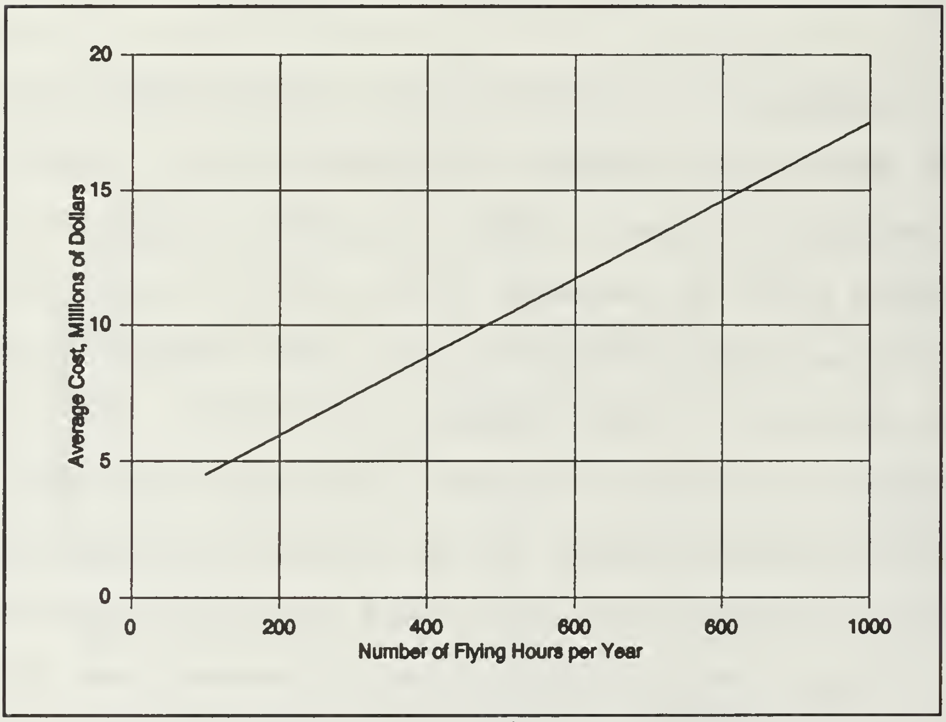

Figure 36: Average Operating Cost Versus Annual Flight Hours

million for a wingship operating 400 hours per year. The flight hours include hours spent training crews, conducting unit or fleet tactical training exercises, maintenance test flights, and contingency operations.

Figures 37 and 38 show the cost sensitivity to fuel cost per gallon. The slope in Figure 38 is $1296 per penny of fuel cost change. This appears significant as an absolute value, but for a ten cent fuel cost increase, the $12960 change represents only a 0.29% increase in annual operating cost. Therefore, wingship operating cost is not significantly sensitive to fuel cost.

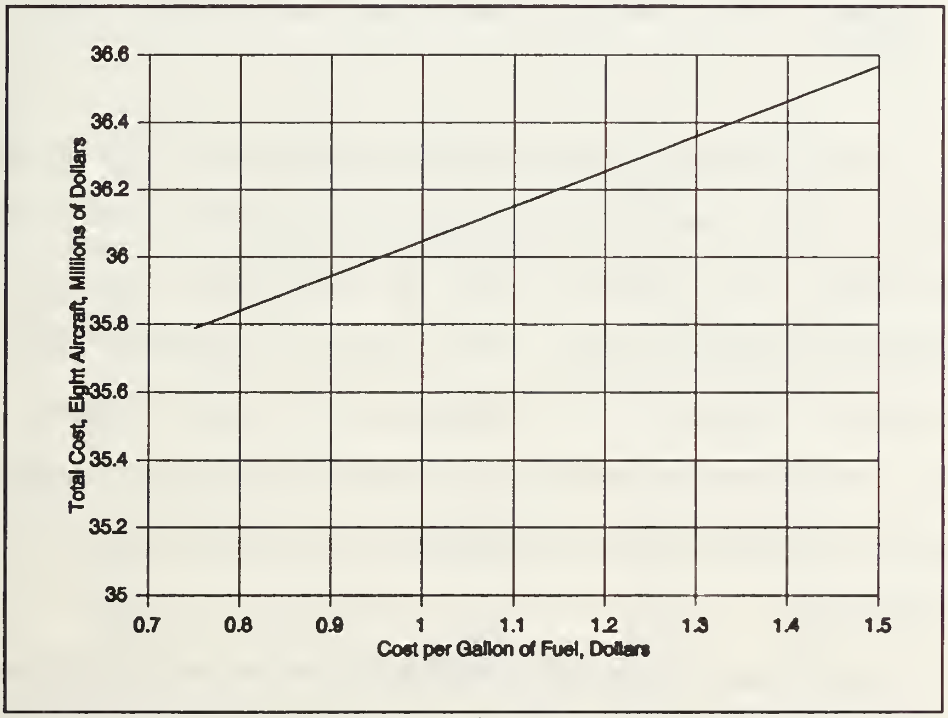

Figure 37: Total Operating Cost Versus Fuel Cost

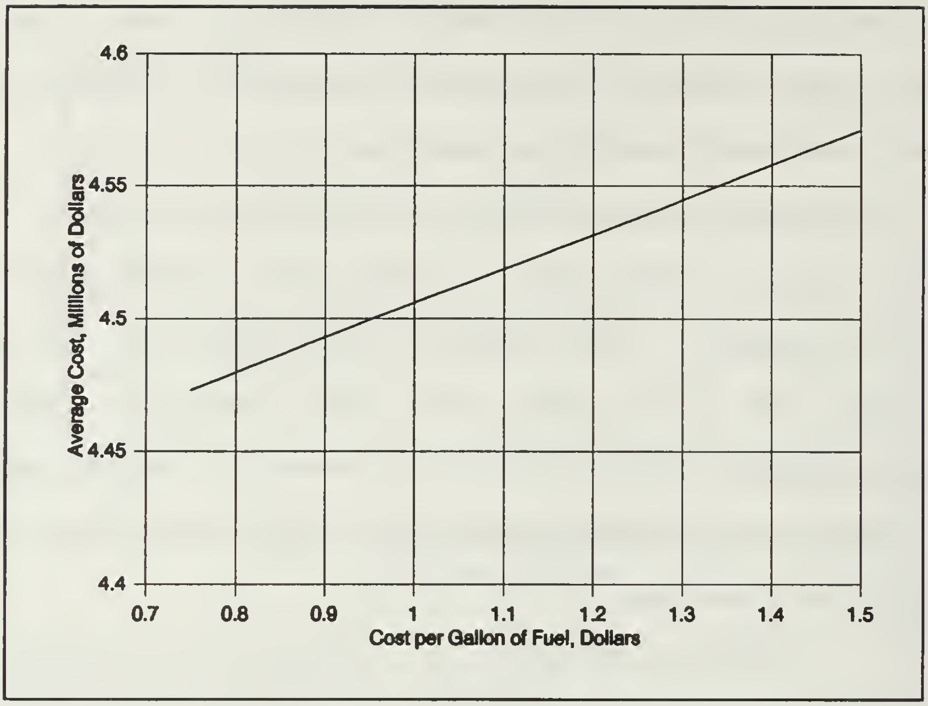

Figure 38: Average Operating Cost Versus Fuel Cost

Cost sensitivity to engine available thrust was also analyzed. The results are shown in Figures 39 and 40. The trend again is linear, with an increased engine thrust increasing wingship cost. The slope in Figure 40 is $32.818 per pound of thrust. An increase in engine thrust of ten percent, from 50000 pounds to 55000 pounds per engine will increase average cost by $164090, or 3.64%. This is a small cost increase.

The final wingship operating cost sensitivity analysis was done on the mean time between engine repairs. Figures 41 and 42 show a non linear decreasing trend. Both graphs show the curves leveling at higher values for Mtbr, and steeper

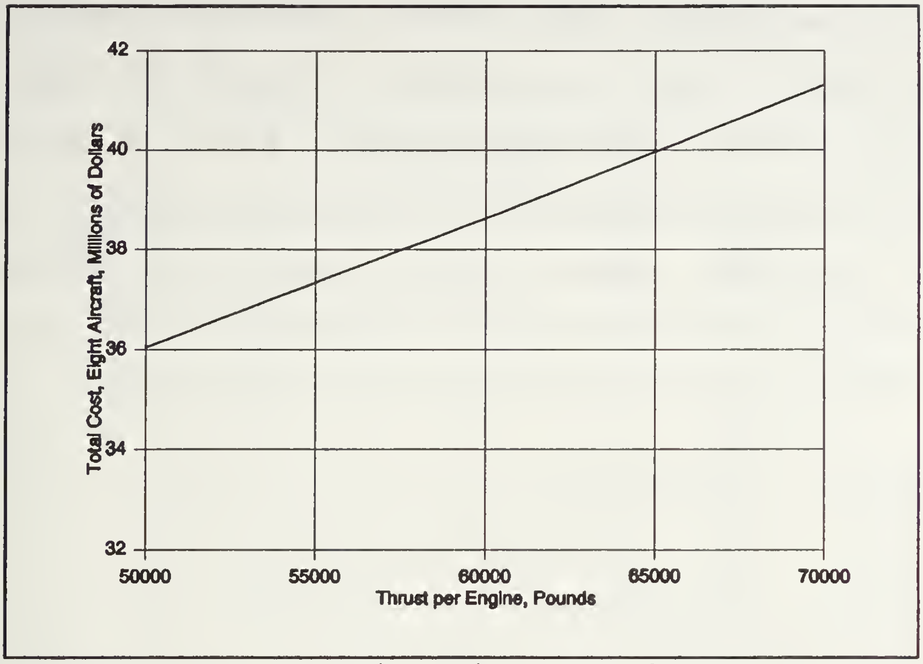

Figure 39: Total Wingship Operating Cost Versus Engine Thrust

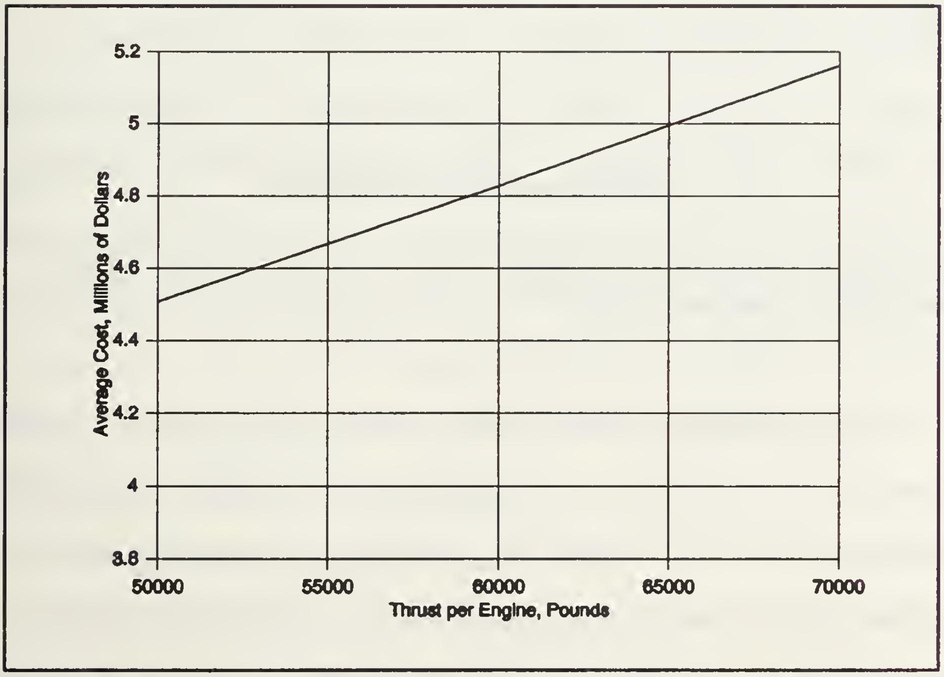

Figure 40: Average Operating Cost Versus Engine Thrust

slopes at the shorter time interval regions on the left side of the figure. Near the baseline value of 100 hours, the slope is - $12958.2 per hour change in Mtbr. A ten percent decrease in Mtbr increases the average wingship cost by $129582, or 2.88%. Again, this is a small cost influence.

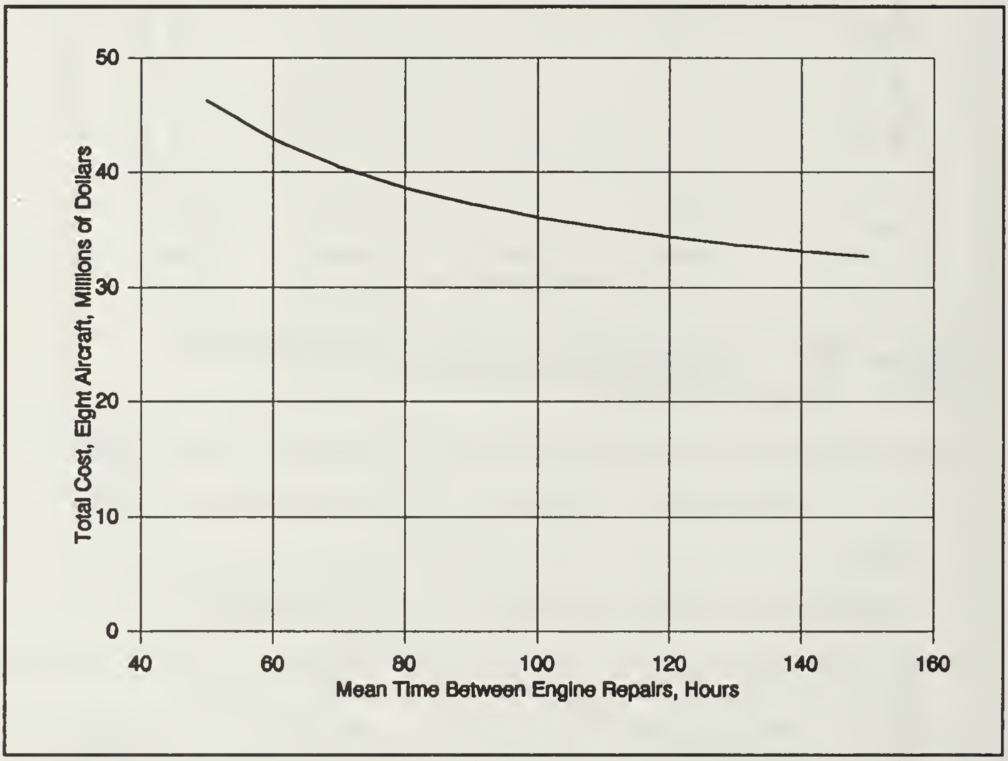

Figure 41: Total Operating Cost Versus Mean Time Between Engine Repairs

This section has shown that the annual wingship operating cost is driven strongly by the number of aircraft in the squadron and the number of flying hours per aircraft per year. The design choice sensitivities, such as engine thrust and reliability, are small cost drivers. Fuel cost was also shown to have a small influence on annual operating cost.

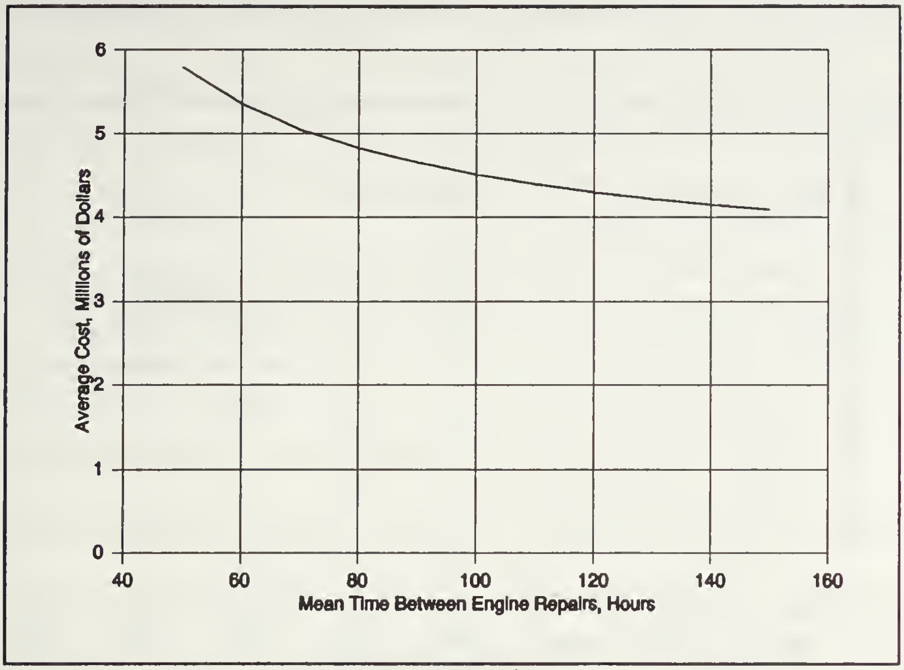

Figure 42: Average Operating Cost Versus Time Between Engine Repairs

4. Surface Ship Operating Costs

Figure 43 shows the annual operating costs for Ticonderoga class cruisers and Arleigh Burke class destroyers as functions of steaming hours. Each curve represents the cost for one ship of its respective class. Note the linear relationship between steaming hours and annual cost for both types of ship. For the baseline case of 1000 steaming hours per ship, a Ticonderoga costs $14.795 million and a Burke costs $12.992 million per year.

5. Comparison of Operating Costs

The baseline annual operating costs for the wingship and surface ships are summarized in Table IX. The individual baselines for each type of vessel was used for this data.

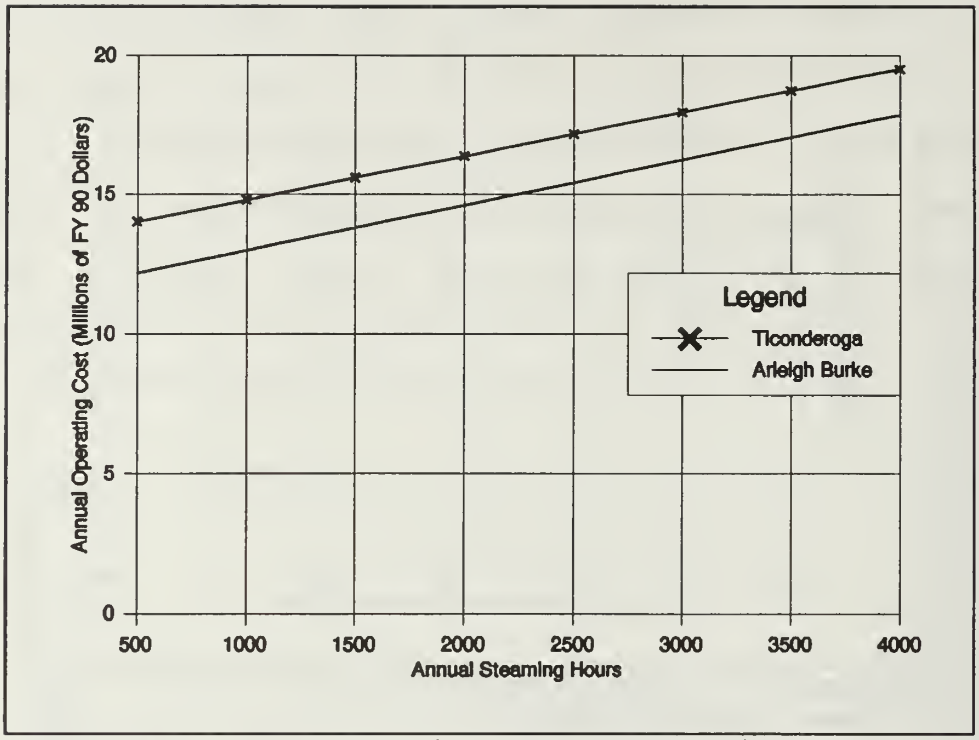

Figure 43: Surface Ship Annual Operating Cost

TABLE IX: BASELINE OPERATING COST COMPARISON

System	Baseline Operating Cost
Wingship	$4.506 Million
Ticonderoga	$14.795 Million
Arleigh Burke	$12.992 Million

These costs can be somewhat misleading, since the baselines are different. Taking a wingship with 1000 flying hours per year, the results will be quite different:

TABLE X: ANNUAL OPERATING COST COMPARISON, 1000 HOURS EACH

System	Annual Operating Cost
Wingship	$139.949 Million
Ticonderoga	$14.795 Million
Arleigh Burke	$12.992 Million

Comparison between Tables IX and X show that setting flight hours equal to steaming hours dramatically increases the wingship annual cost. A direct comparison between flight and steaming hours is not appropriate, since a surface ship spends nearly all its operational time steaming, while the wingship does not spend all of its mission time flying (due to prolonged periods of sea sitting).

Figure 44 shows the data of figures 36 and 43 on the same axes. It shows a crossover point of equal costs at 655 hours for the destroyer and 790 hours for the cruiser. This figure shows that at the above listed wingship flight hours, their cost to operate are the same as that of the surface ships. Obviously, if the annual flight hours are less, the wingship will be cheaper to operate, and if they fly more hours, they will be more expensive. A better comparison relies on analyzing the military benefits obtained for these costs. Chapter VI contains this discussion.

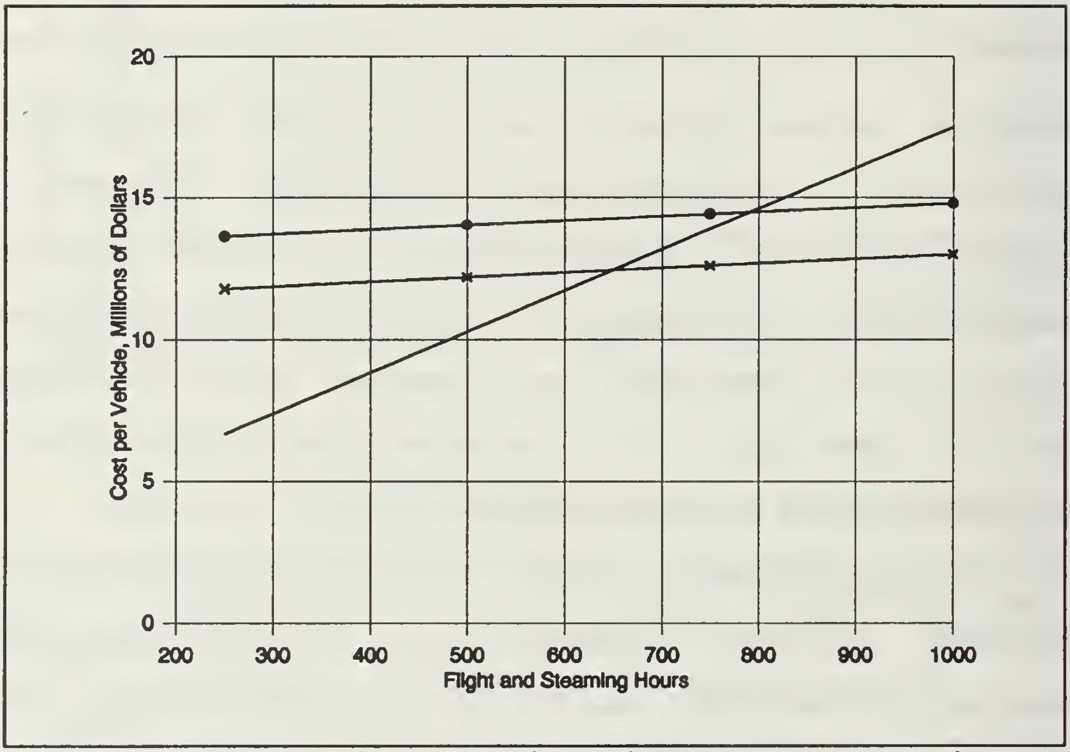

Figure 44: Comparison of Wingship and Surface Ship Operating Costs

VI COST EFFECTIVENESS

A. INTRODUCTION

This chapter will combine the results of the tactical and cost analyses to determine whether the proposed combatant wingship is cost effective. Chapter II showed that there is a tactical use for the capabilities offered by the wingship, and Chapter V showed that the wingship is somewhat more expensive to develop, manufacture, and operate than the surface ships. Using deployment speed and cost as components of a figure of merit, the consolidated cost effectiveness will be determined.

B. EFFECTIVENESS COMPARISON

The effectiveness figure of merit chosen for this comparison is the number of missiles carried divided by the time required to travel a designated distance. Thus, a vessel with a large number of missiles covering the deployment distance quickly would have a higher measure of effectiveness than a slower, less well armed vessel. This figure of merit assumes that all vehicles will have the same capabilities in the mission area (fire control, sea keeping, survivability). These will be different for real vehicles, but for simplicity in this stage of the analysis, they will be held constant here.

Figure 45 shows the effectiveness figure of merit versus deployment range. The two surface ships, with identical weapons capabilities and nearly identical speeds, have coincident curves at the figure's scale. The two wingship models shown are the 48 missile air defense wingship and the 32 missile cruise missile or NTACMS carrier. They both show consistently higher effectiveness, most noticeably at the smaller deployment ranges.

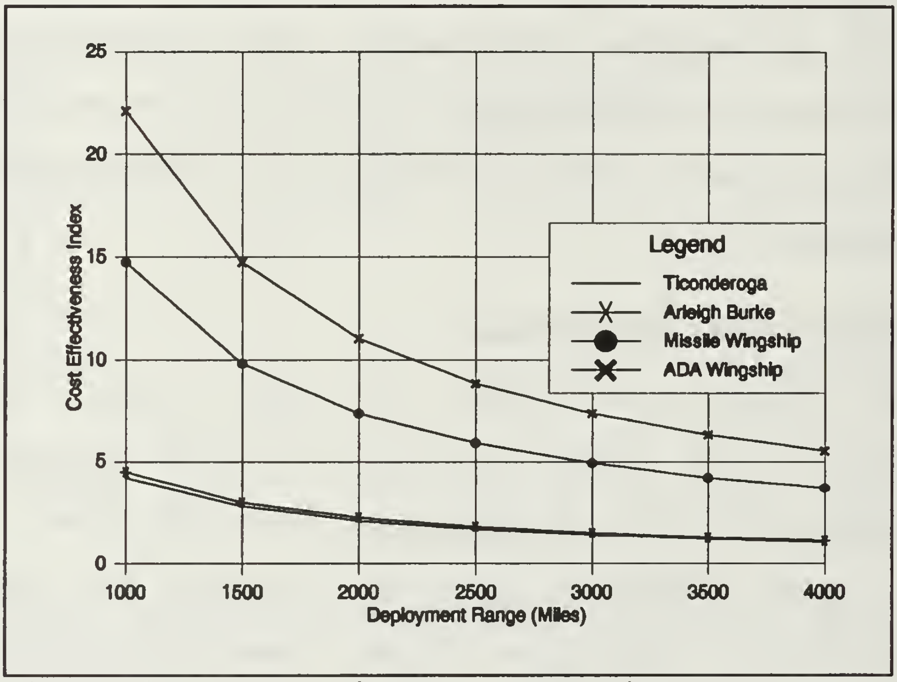

Figure 45: Effectiveness Comparison

This restates the conclusion of Chapter II regarding wingship effectiveness. The next section will include operating cost and program cost into the figure of merit.

C. COST EFFECTIVENESS COMPARISON

The figure of merit chosen for this comparison is the same one used in Section VI(B) above, divided by a representative cost. Both the annual operating costs and program costs are used.

Figure 46 shows the cost effectiveness figure of merit. The baseline vehicles are plotted, with 1000 as the surface ship steaming hour baseline and 100 hours for the wingship flight hour baseline.

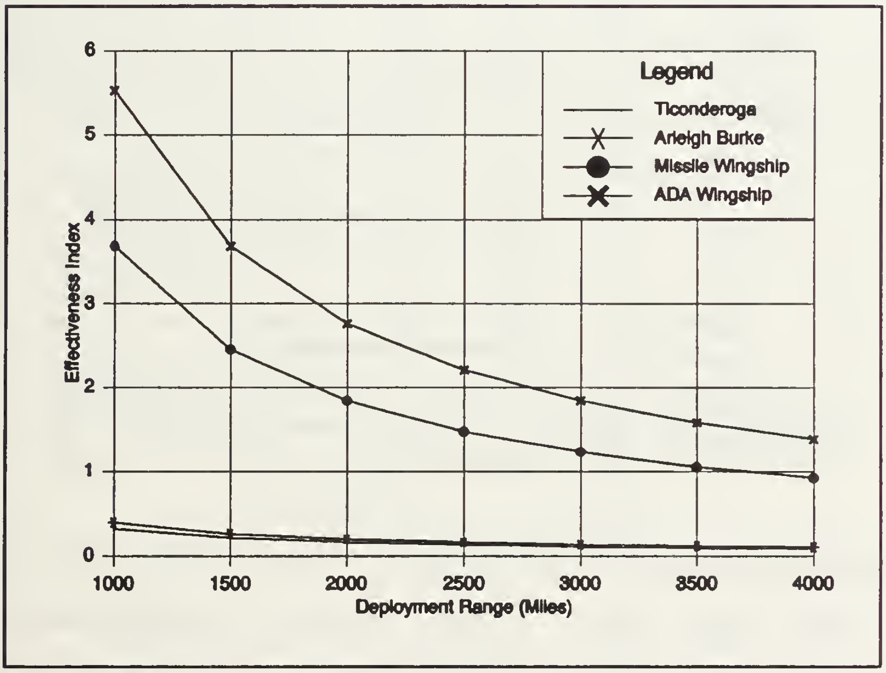

Figure 46: Cost Effectiveness of Baseline Vehicles

Again, the two wingships score higher than the surface ships. This is to be expected, since the baseline wingship's annual operating cost (in a squadron of eight aircraft) is \$4.506 million, versus \$12.992 million for the Arleigh Burke

class and $14.795 million for the Ticonderoga class. Figure 47 shows the wingship extreme case, with 1000 annual flight hours, and an annual operating cost of $139.949 million. This dramatically higher operating cost places the wingships below the surface ships.

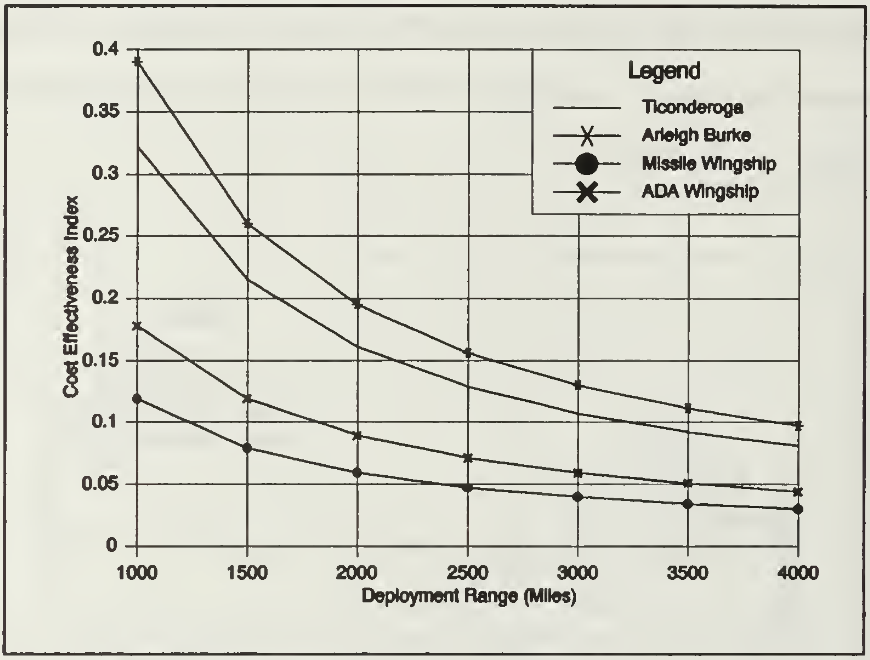

Figure 47: Cost Effectiveness of Vehicles, 1000 Hours Each Per Year

Comparing Figures 46 and 47 shows that the number of flight hours per year for the wingship determines its cost effectiveness. If the required number of flight hours remains below approximately 940 hours per year, the wingship will be cost effective compared to surface ships. A wingship could execute 47 missions of 20 hours each in 940 hours. Current aircraft do not operate this much, and a wingship probably would not either.

Figures 48 and 49 show the same cost effectiveness figure of merit, but using the average program cost per wingship and warship instead of the annual operating cost. Figure 48 uses the lower bound wingship cost ($2.796 billion) and Figure 49 uses the upper bound wingship cost ($6.608 billion). Here the results are much closer than those shown in Figures 46 and 47. In Figure 48, the missile carrier wingship is nearly coincident with the Burke class destroyer. The speed advantage of the wingship offsets the additional cost. As shown in Figure 49, the upper bound cost places the wingships below the surface ships. Since the actual wingship cost will

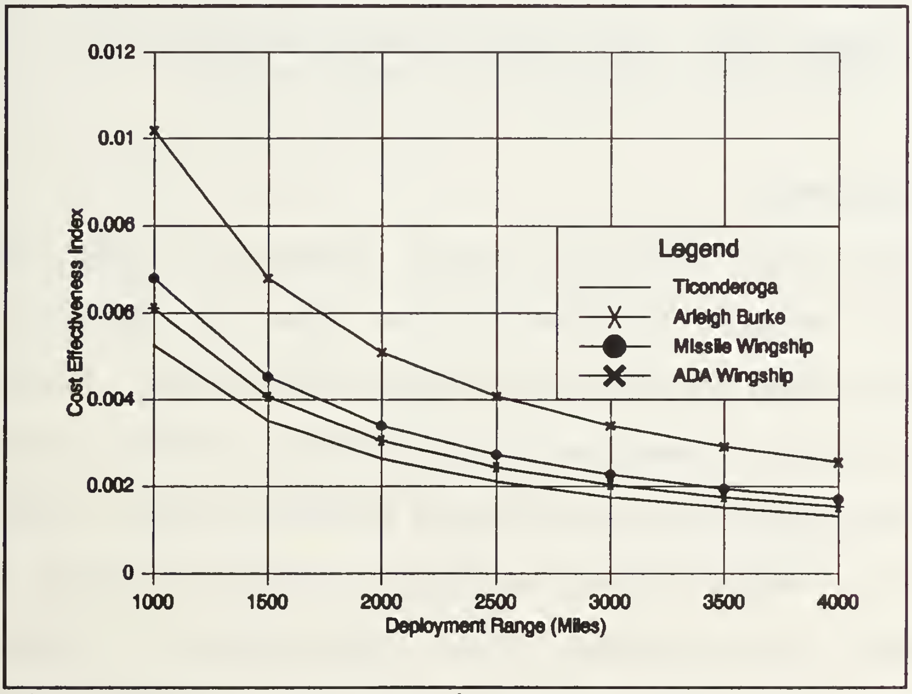

Figure 48: Cost Effectiveness Measured By Individual Program Cost, Lower Bound

probably be somewhere between the two bounds, the actual effectiveness would have figures of merit nearly the same as those of the surface ships.

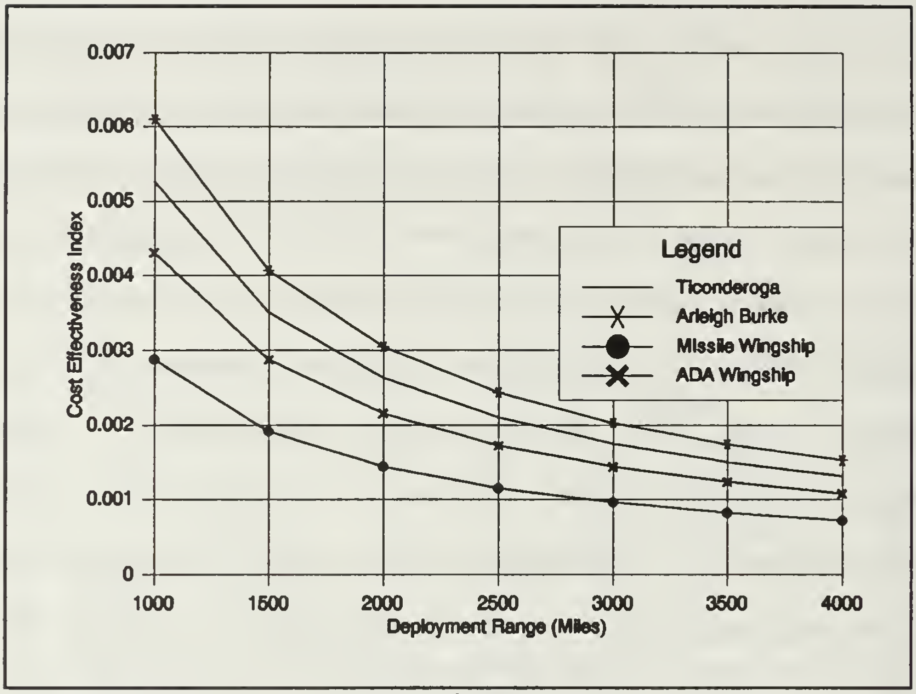

Figure 49: Cost Effectiveness Measured by Individual Program Cost, Upper Bound

D. CONCLUSION

Using the figure of merit defined as the number of missiles carried divided by the time to travel a given distance times the cost (operating or program), the wingship came out nearly identical to the surface warships currently in use. The operating cost measure showed the most variability, so force planners must carefully estimate annual wingship training, maintenance, and operational flight hour requirements before committing to a purchase decision. Operational concerns may dictate more hours than those planned for, which drives the wingship below the surface ships on the figure of merit charts. Ship costs are also variable, and

they vary in ways analogous to the wingship, so this effect should cancel. Thus, the 1000 ton combatant wingship is a cost effective competitor to current Navy warships.

VII CONCLUSION

This report has shown that the wingship provides a revolutionary combat capability to the Navy at a cost competitive with the costs of Ticonderoga class cruisers and Arleigh Burke class destroyers. Technical considerations must be addressed before committing wingships to an operation, and must be included in the design process. The wingship provides a cost effective means of accomplishing the four design missions, while surface combatants provide a very flexible platform for the accomplishment of several other missions, such as forward presence, strategic deterrence, or humanitarian at-sea rescue. These missions were beyond the scope of this thesis, but must be considered in any final comparison between wingships and surface warships.

Tactically, the wingship can accomplish the cruise missile, air defense, and mine warfare missions in a manner similar to the surface combatants, but with a much faster deployment speed. It can do the same missions, and can get to the mission area much quicker. A concern is that a wingship has a design maximum sea state, which could prevent their use in a location with frequent severe storms.

Technically, the wingship must be designed for numerous takeoffs and landings from the sea surface, and it must be capable of sustained operations in the corrosive sea

environment. The wingship is much larger than any current aircraft, so the question of size and manufacturability must also be considered.

Financially, the wingship will cost between $2.796 and $5.608 billion per aircraft, which exceeds current aircraft and combatant ships. The operating costs are competitive with those of today's warships. Including a measure of effectiveness, the wingship becomes cost competitive with the Ticonderoga and Arleigh Burke class ships.

Since the wingship requires a significant research and development effort prior to actually building and operating one, the costs will begin several years before the benefits are realized. Force and budget planners must decide if the future benefits are worth the initial costs. Continued research into wingship technology would reduce the risk, and reduce development time if the decision is made to build a wingship at a later time.

APPENDIX A: COST ANALYSIS VALIDATION

A. INTRODUCTION

In Reference 18, the author uses the example of the Cessna Citation to validate the cost estimating relations. The relevant data are as follows:

1. Time = 1974 (Inflation multiplier 1.3)
2. AMPR weight = 3800 pounds
3. Speed = 412 knots
4. Q_D = 3
5. Q_P = 250
6. Flight test rate = 3 per month
7. Production rate = 10 per month
8. Engines = 2 JT15D, 2500 pounds thrust each

B. COMPARISON

The example values and the calculated values are shown in Table XI. The same cost estimating relations are the same for both columns. Any difference can be explained by either an error or rounding differences.

TABLE XI: NICOLAI COST VALIDATION RESULTS

Item	Reference 18 CER	Chapter 5 CER
DT and E Costs:		
Airframe Engineering	$6,281,982	$6,281,988
Development Support	$1,848,070	$1,848,070
Flight Test Operations	$361,018	$359,857
Tooling	$8,322,230	$8,322,227
Manufacturing Labor	$6,584,539	$6,584,539
Quality Control	$855,990	$855,990
Manufacturing Material	$998,734	$998,734
Engines	$1,146,600	$538,782
Total DT and E Costs	$26,399,162	$25,790,190
Production Costs:		
Sustaining Engineering	$7,830,615	$7,861,449
Tooling	$12,966,282	$13,011,530
Manufacturing Labor	$60,674,248	$60,674,250
Quality Control	$7,887,657	$7,887,652
Manufacturing Material	$32,485,569	$32,485,570
Engines	$63,700,000	$44,898,520
Total Production Cost:	$185,544,371	$166,818,971
Total Program Cost:	$211,943,533	$192,609,161

Note the only significant difference between the two involve engine cost. The reference used a fixed engine cost,

while the program used in the Chapter V cost analysis used the exponential form shown in the Nicolai CER listing.

For comparison, the Rand recommended method gave a total cost of $333,414,800. This is almost twice as high as the Nicolai result, which is consistent with the Chapter V trends. The DAPCA III cost for this data set is $214,973,100.

APPENDIX B: COST COMPONENT CONTRIBUTIONS

Chapter V contained an analysis of wingship and surface ship program and operating costs. This appendix will show the breakdown by component of the baseline cases for each cost model.

A. PROGRAM COST

1. Nicolai Method

The Nicolai method contains separate calculations for the DT&E and production phases of the wingship program. Figure 50 shows the contribution of the major components to the baseline DT&E program cost:

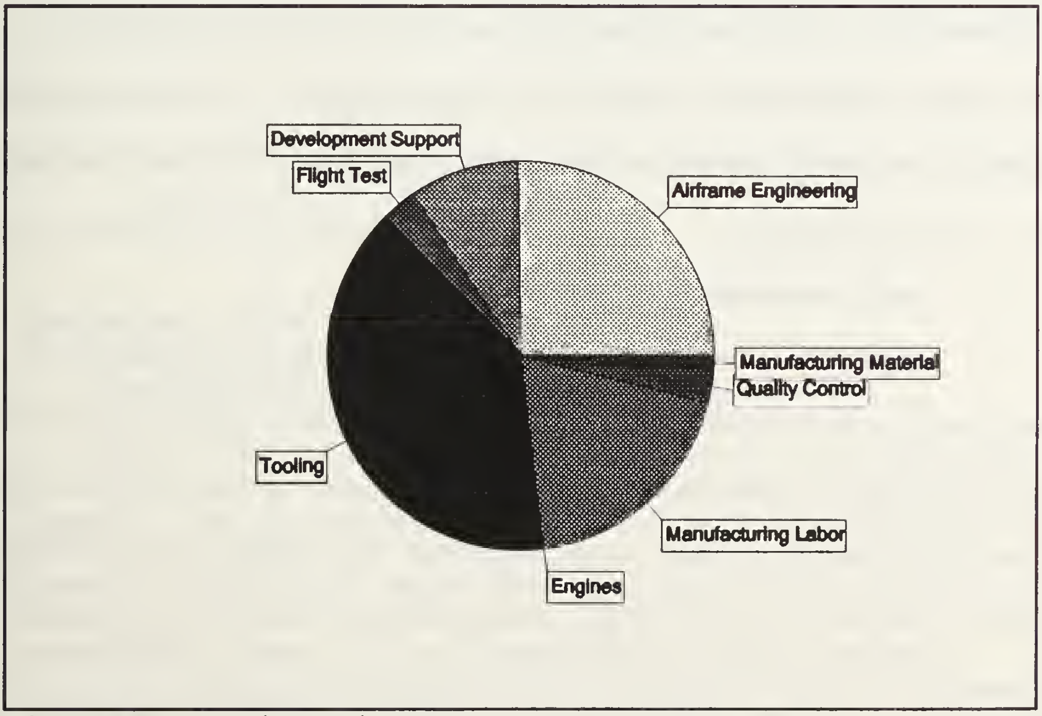

Figure 50: Nicolai DT&E Cost Components

Figure 51 shows the cost components during the production phase for the same baseline wingship:

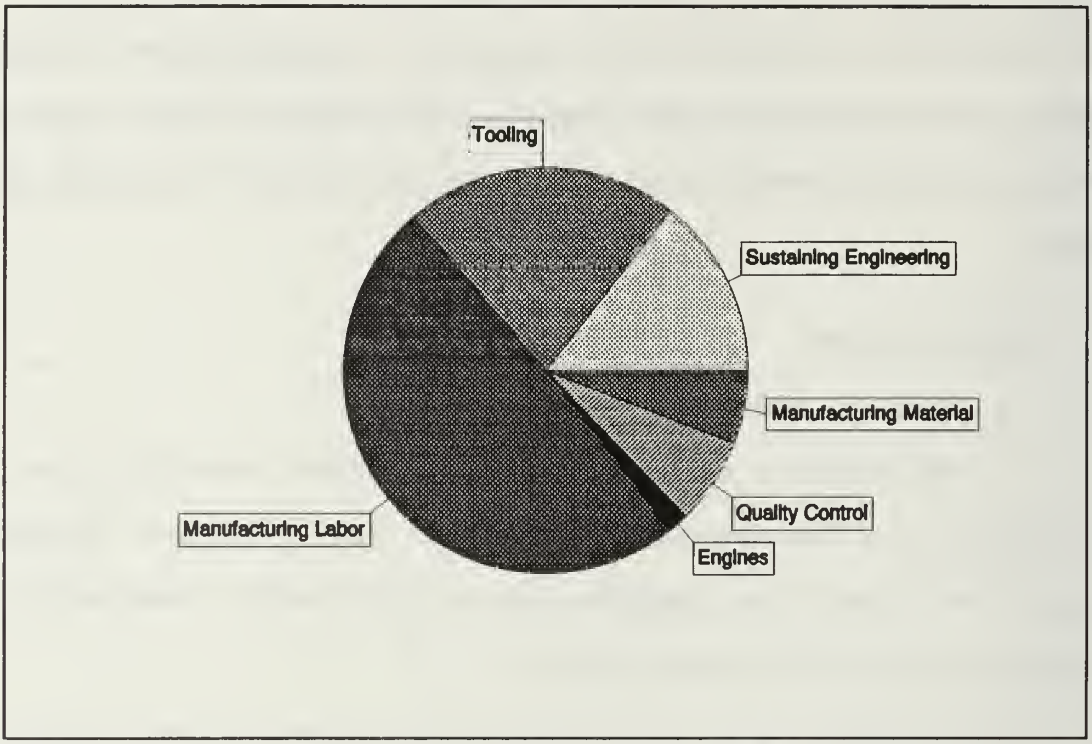

Figure 51: Nicolai Production Phase Cost Components

Note the relatively small contributions of manufacturing material in both cases. Labor and tooling provide the largest cost contributions.

2. Rand Recommended Method

Figure 52 shows the cost contributions of the components of the Rand recommended method. Note the dramatic contribution of manufacturing labor costs to the overall cost. Since this method does not isolate the DT&E and production phases, the contribution of engineering costs to the total can be seen.

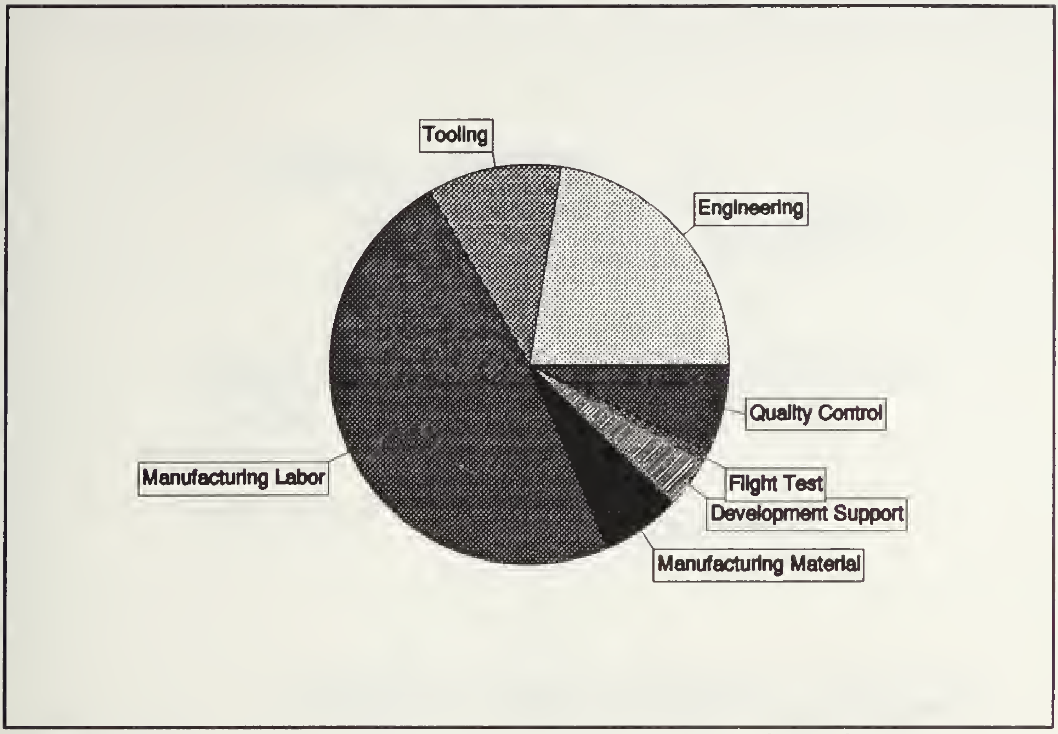

Figure 52: Rand Recommended Cost Contributions

3. DAPCA III Method

Figure 53 shows the contributions of the component elements to the total program cost for the baseline wingship using the DAPCA III method. Again, engineering, tooling, and labor dominate the overall cost.

B. OPERATING COSTS

1. Surface Ship Operating Cost

Figure 54 shows the component cost contributions to the overall annual operating cost for an Arleigh Burke class destroyer. Figure 55 shows the component contributions for the operating costs of a Ticonderoga class cruiser. Both figures show that personnel costs provide most of the annual

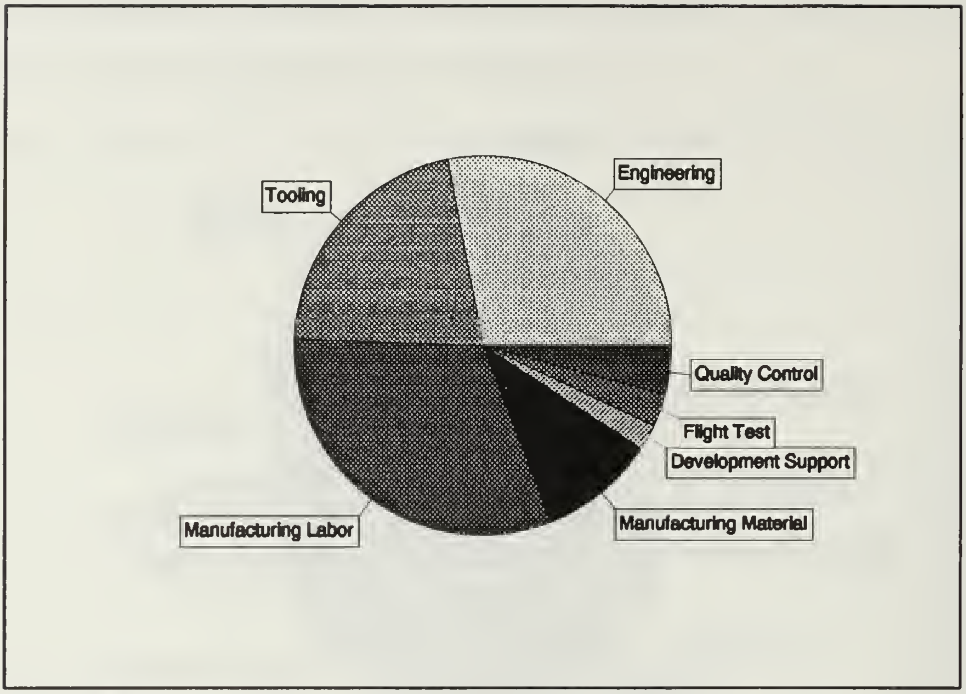

Figure 53: DAPCA III Cost Components

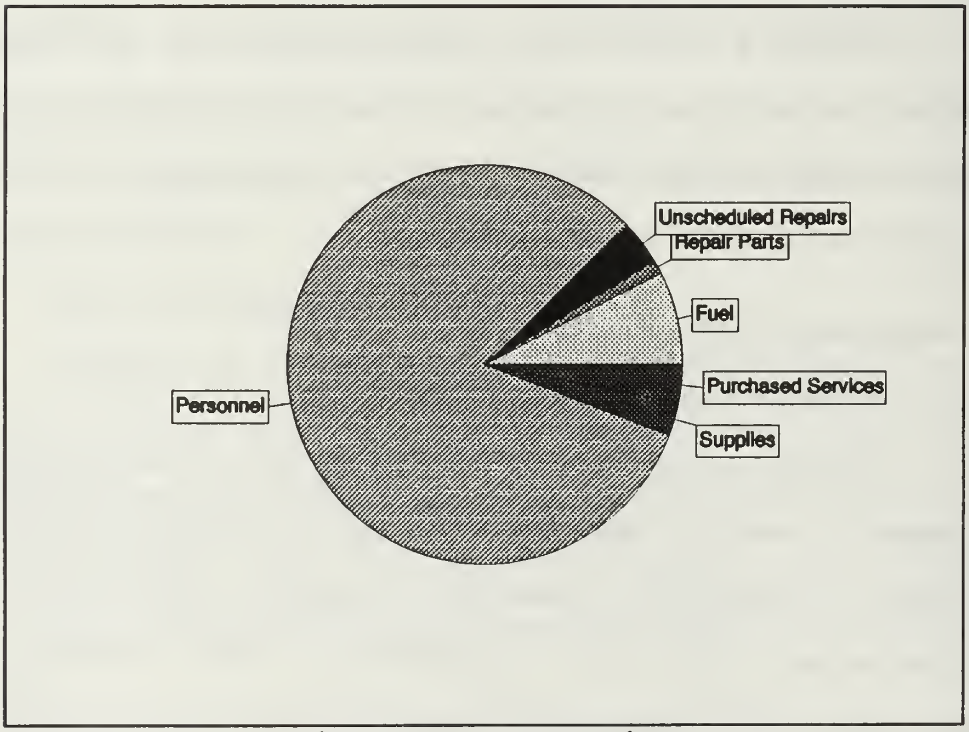

Figure 54: Arleigh Burke Operating Cost Component Contributions

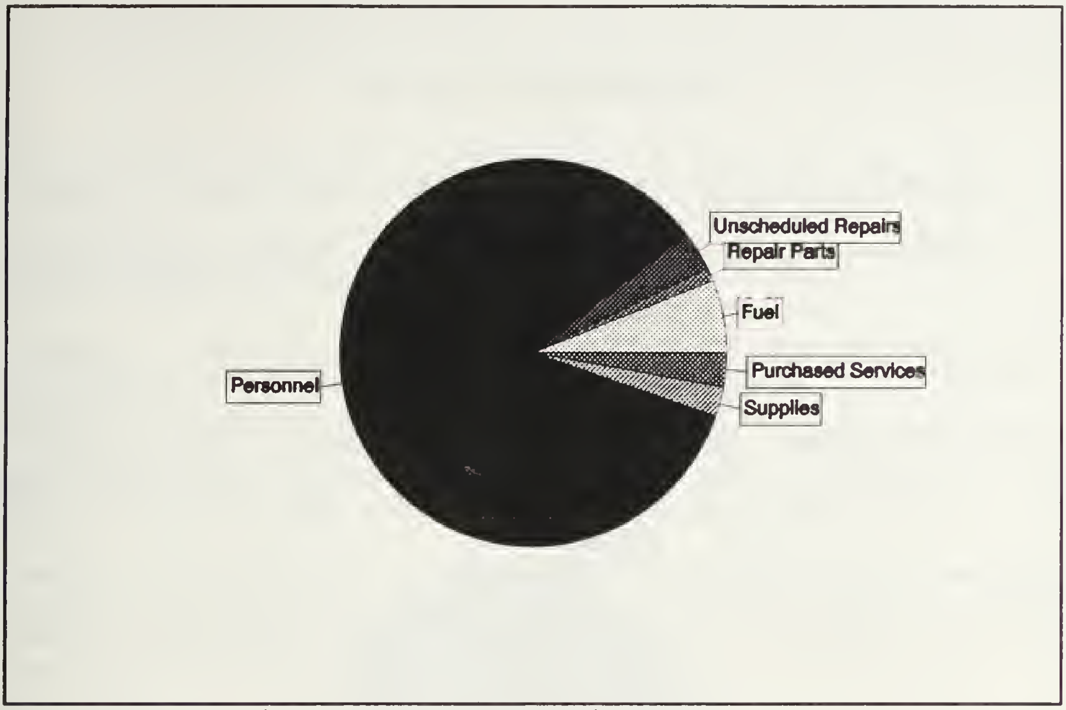

Figure 55: Ticonderoga Operating Cost Component Contributions

cost for a surface ship. Intermediate maintenance and temporary additional duty costs were omitted due to the tiny contribution from these sources.

2. Wingship Operating Cost

Figure 56 shows the component contributions to the annual operating cost for the baseline wingship. Again, personnel costs provide the largest single contribution to the overall cost. Engine rework is also a major component, as expected for a vehicle with eight engines. The cost model does not account for the adverse wingship operating environment, so engine costs may actually be higher than shown.

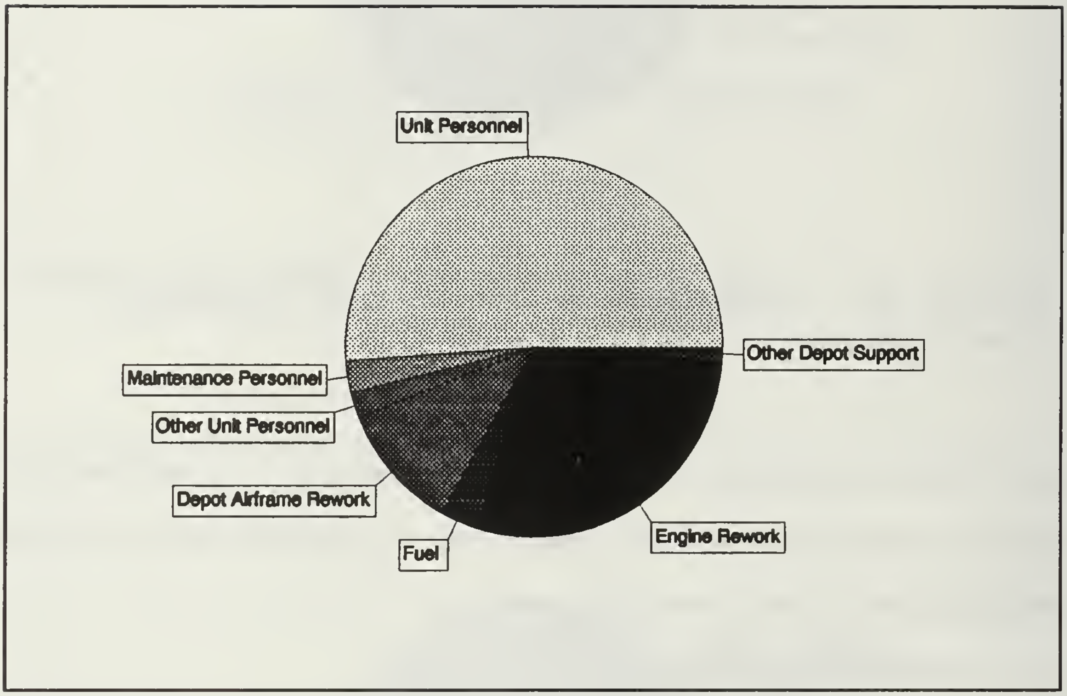

Figure 56: Wingship Operating Cost Component Contributions

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